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FLIGHT COMPARISON OF THE TRANSONIC AGILITY OF THE F-111A AIRPLANE AND THE F-111 SUPERCRITICAL WING AIRPLANE

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SUMMARY

A flight research program was conducted at the Dryden Flight Research Center (DFRC) to investigate the improvements in maneuverability that resulted when an F-111A airplane was equipped with a supercritical wing. (The supercritical wing airplane is known as the F-111 TACT (transonic aircraft technology) airplane.) The approach undertaken in the study was first to evaluate the aerodynamic performance, maneuver performance, and degree of precision controllability of the F-111A airplane at selected flight conditions and wing-sweep positions. The wing-sweep positions selected for the flight program were 26°, 35°, and 58°. Then a similar program was flown with the F-111 TACT airplane to permit an assessment of the difference due to the supercritical wing. The aerodynamic performance, maneuver performance, and precision controllability of both airplanes are summarized, and an overall comparison of the two airplanes is made by using an agility assessment technique developed at DFRC.

The aerodynamic performance evaluation showed that the supercritical wing significantly improved the buffet characteristics of the F-111A airplane at transonic speeds. The F-111A buffet boundaries decrease as Mach number increases from subsonic to transonic speeds for the more forward wing-sweep positions. The F-111 TACT buffet boundaries are nearly constant with increasing Mach number for the wing-sweep positions investigated, and they are better than the F-111A boundaries at transonic speeds.

The maneuver performance evaluation showed that the F-111 TACT airplane had improved drag-rise Mach number characteristics at a 26° wing-sweep position and improved sustained turn performance at all wing-sweep positions for transonic speeds. The addition of the supercritical wing did not significantly degrade the aircraft's supersonic performance characteristics.

The precision controllability evaluation showed that the airplanes were similar at subsonic speeds. At transonic speeds, where the differences in the buffet

characteristics were large, the piloting task was found to be less demanding for the F-111 TACT airplane. Wing rock was exhibited by both airplanes, the F-111 TACT aircraft having the higher boundary.

The agility assessment demonstrated that the overall performance of the F-111 TACT airplane at transonic speeds was significantly better than that of the F-111A airplane.

INTRODUCTION

Maximizing transonic maneuverability is essential for air superiority aircraft. The high turn rates required for maneuverability result in flight at high angles of attack, which normally causes flow separation on the wing. The flow separation leads to increased drag, buffet, and stability and control problems that degrade the aircraft's combat capabilities. The stability and control problems may develop gradually or involve sudden roll, yaw, or pitch rate oscillations that are difficult for the pilot to control. Flight and wind-tunnel studies have been conducted or sponsored by government agencies on many present day aircraft, and the buffet characteristics and resulting handling qualities deficiencies of these aircraft are fully documented (refs. 1 to 6). These studies illustrated the advantages that variations to twist, camber, and sweep have on the wing flow characteristics. However, the use of these methods alone does not fully solve the basic supercritical flow problem.

Two-dimensional wind-tunnel tests for supercritical airfoils indicated that substantial improvements in aircraft performance at high subsonic speeds might be achieved by shaping the airfoil to improve the supercritical flow above the upper wing surface (ref. 7). Subsequent wind-tunnel studies investigated the effects of the application of a supercritical airfoil to a variable-wing-sweep multimission airplane (ref. 8).

After these exploratory investigations, a cooperative government/contractor wind-tunnel program was initiated to determine the aerodynamic advantages in aircraft maneuverability that could be realized through the application of supercritical airfoil technology to the F-111A airplane. In anticipation of an eventual full-scale flight validation of the wind-tunnel results, program objectives and constraints were established to allow for a practical design. The objectives of the program were as follows: (1) to maximize the transonic maneuver capability of the F-111A airplane without degrading its cruise performance; (2) to minimize degradation in sea-level dash and supersonic performance; and (3) to maintain existing F-111A takeoff and landing performance. The design constraints generally consisted of limiting major airframe modifications to the outboard wing panels and the wing glove. Reference 9 documents the preliminary research done for the development of the wind-tunnel program.

This report presents the agility characteristics of the F-111A and F-111 TACT (for transonic aircraft technology) airplanes. First the F-111A airplane was flown in a baseline configuration to establish a data reference. The same airplane was then

flown with a supercritical wing. The aircraft's agility was assessed through combined studies of buffet (separated flow), precision control (gunsight tracking), and energy/maneuverability (specific excess power). The results of these studies are presented individually, and selected data are shown in combination to permit an assessment of overall aircraft agility. Comparisons are made for wing-sweep positions of 26°, 35°, and 58° over the transonic Mach number range.

SYMBOLS AND ABBREVIATIONS

Physical quantities in this report are given in the International System of Units (SI) and parenthetically in U.S. Customary Units. The measurements were taken and the calculations were made in U.S. Customary Units. Factors relating the two systems are presented in reference 10.

AR	aspect ratio
a_l	longitudinal acceleration, g
a_n	normal acceleration, g
b	airplane wingspan, m (ft)
C_L	airplane lift coefficient
C_{N_A}	airplane normal-force coefficient
h_p	pressure altitude, m (ft)
M	Mach number
PCM	pulse code modulation
PIO	pilot-induced oscillation
PLA	power lever angle
PSD	power spectral density
p	rolling angular velocity, deg/sec
p_s	specific excess power, m/sec (ft/sec)
$\bar{q}$	dynamic pressure, N/m^2 (lb/ft^2)
rms	root mean square

S	wing area, m^2 (ft^2)
TACT	transonic aircraft technology
t	time, sec
t/c	wing thickness-to-chord ratio
V	true velocity, m/sec (ft/sec)
V_i	cockpit indicated velocity, knots
W	airplane weight, N (lb)
W.S.	wing station, cm (in.)
α	calibrated angle of attack, deg
β	calibrated angle of sideslip, deg
δ	control surface deflection, deg, or control stick deflection, cm (in.)
ε	rms value of gunsight tracking miss distance, mils
Λ	leading-edge wing sweep, deg
λ	taper ratio
σ	rms value of buffet component of normal acceleration, g
$\bar{\sigma}$	normalized value of buffet component, $\frac{\sigma}{\sqrt{\bar{q}/\bar{q}_{ref}}}$, g
Φ	power spectral density value of buffet component of associated quantity, g^2/Hz
φ	bank angle, deg

Subscripts:

a	asymmetrical deflection of the elevons, deg
bir	buffet intensity rise
cg	center of gravity
ckpt	cockpit

init	initial
M_{cr}	critical Mach number (drag-rise Mach number)
$p_s=0$	sustained turn specific excess energy
ref	reference
st	control stick
wro	wing rock onset
wt	wingtip

AIRCRAFT DESCRIPTION

F-111A Airplane

The F-111A airplane is a two-place (side by side) long-range fighter bomber. Power is provided by two TF30-P-3 axial flow, dual-compressor turbofan engines equipped with afterburners. The wings, which are equipped with leading-edge slats and double-slotted Fowler flaps, may be varied in sweep angle between 16.0° and 71.5°. The empennage consists of a fixed vertical stabilizer with a rudder for directional control and a horizontal stabilizer (rolling tail) that is moved symmetrically for pitch control and asymmetrically for roll control. The flight control system incorporates pilot-assist modes, command augmentation (rate command and adaptive gain scheduling in pitch and roll), and a fixed-gain yaw damper. In pitch and roll, the command augmentation and adaptive gains are designed to provide invariant aircraft response for pilot control throughout the operational envelope within the limits of control-system authority. The augmentation system commands roll rate as a function of stick position. For wing-sweep positions greater than 45°, only the rolling tail provides roll control power. For wing-sweep positions less than 45°, roll control power is augmented by two sets of spoilers, which can be deflected a maximum of 43°. The spoilers are first activated at a lateral stick displacement of approximately 1.27 centimeters (0.5 inch). The spoiler schedule is nonlinear, with maximum spoiler deflection occurring at a 5.72-centimeter (2.25-inch) stick displacement, or approximately one-half the total stick displacement. Augmentation-off flight is considered to be outside the normal flight environment of the aircraft. The flaps cannot be extended at wing-sweep positions greater than 26°, and the rotating glove can be operated only with the flap system.

An inlet is provided for each engine below the intersection of the wing and fuselage. Features of the propulsion system include splitter plates for bleeding off low energy boundary layer air, spikes that modulate fore and aft to vary inlet geometry, and translating cowls for the matching of air intake with engine requirements.

F-111 TACT Airplane

The same airplane used for the baseline flight program was modified to incorporate the supercritical wing (fig. 1). The airframe modifications included a new high lift system, a new spoiler configuration, modified overwing fairings, modified wing seals, and a new nonrotating wing glove. The supercritical wing was designed to be within the structural and other physical limits of the existing wing pivot and wing carrythrough structure. As part of the attempt to increase maneuverability, the planform area of the supercritical wing was increased over that of the basic wing. Wingspan and aspect ratio were decreased accordingly to limit the bending moments at the wing pivot to the allowable stress levels for the existing wing pivot and carrythrough structure.

Glove contours near the wing-glove leading edge were slightly different for the supercritical wing than for the conventional wing because of the larger leading-edge radius of the supercritical wing. The overwing fairing and wing seal were also redesigned to accommodate the new airfoil.

A new high lift system was designed to permit the F-111 TACT airplane to meet the F-111A low speed takeoff and landing performance. Emphasis was on simplicity of design. The resulting flap system included a Krueger leading-edge flap and a single-slotted Fowler trailing-edge flap. The flap system was not used or designed for maneuvering flight.

The flight control system was not changed for the F-111 TACT airplane except for the different range of wing-sweep positions available and different wing spoiler usage. The design changes in the wing restricted wing-sweep positions to a maximum of 58°. The spoilers were operable over the available range of wing-sweep positions.

Plan views and airfoil section properties for the test airplanes are shown in figure 2. Figure 3 shows the changes in wing geometry that accompany changes in wing-sweep position. The physical characteristics of the wings, high lift systems, and spoilers are listed in table 1.

INSTRUMENTATION AND DATA ACQUISITION SYSTEM

The data acquisition system used for this flight program was a flexible airborne pulse code modulation (PCM) system that operated in conjunction with the onboard recording and telemetry systems. The prime commutator of the PCM system can sample 77 data channels at 200 samples per second, and additional data channels can be obtained through subcommutation. For the F-111 TACT airplane, this feature provided 316 subcommutation channels at 20 samples per second and 45 channels at 200 samples per second. A 40-hertz cutoff frequency was provided for the 45 channels of the prime commutator to preclude aliasing errors. The channels obtained from subcommutation were provided with a 10-hertz cutoff frequency.

Each airplane was equipped with conventional stability and control instrumentation for the evaluation of aerodynamic and maneuver performance and overall

handling qualities. The nose-boom-mounted air data system described in reference 11 was utilized for the entire flight test program for the measurement of both total and static pressure, angle of attack, and angle of sideslip. In addition, high frequency response accelerometers and semiconductor strain gages were mounted on the wings of the aircraft for the evaluation of wing flow separation phenomena.

The stability and control parameters were sampled at 20 samples per second, whereas the high frequency response parameters were sampled at 200 samples per second. The high frequency response parameters were high pass filtered through the onboard instrumentation system so that only the airplane structural response frequencies were measured, thus providing the full range of the PCM system for maximum resolution. A fixed-reticle gunsight and camera were installed to permit the evaluation of precision control during tailchase tracking maneuvers.

The angle of attack and angle of sideslip vanes mounted on the aircraft nose boom and the three-axis accelerometers mounted near the airplane center of gravity were corrected for angular rates and accelerations. Angle of attack was measured relative to the nose-boom centerline but referenced to the wing pivot chord line. The correction for angle of attack vane nose-boom upwash may be found in reference 11, and fuselage and wing upwash corrections were determined as described in references 12 and 13, respectively. No fuselage flexibility correction was applied to the corrected angle of attack.

FLIGHT CONDITIONS

The prime flight conditions considered in this study consisted of a test corridor at a constant dynamic pressure of 14.4 kN/m^2 (300 lb/ft^2) and at Mach numbers from 0.70 to 0.95. This test corridor was chosen on the basis of aerodynamic and structural considerations to insure that the limit angle of attack (15° for the forward and intermediate wing-sweep positions (up to 45°); 18° for wing-sweep positions greater than 45°) could be obtained within the g limits of the aircraft. In addition, data were obtained at the F-111 TACT design point; that is, $M = 0.90$, $h_p = 3.05$ kilometers (10,000 feet), and $\Lambda = 26°$. The corresponding dynamic pressure was approximately 38.3 kN/m^2 (800 lb/ft^2). Figure 4 indicates the range of flight test conditions covered in this study. Data were obtained for both airplanes for wing-sweep positions of 26°, 35°, and 58°. The symbols in the figure indicate the primary flight points where the agility analysis was conducted. Aerodynamic and maneuver performance data were obtained at Mach numbers from 0.60 to 0.95. Specific excess power data were obtained from 1g level accelerations at Mach numbers from 0.60 to 1.60.

The maximum takeoff weight for both the F-111A and F-111 TACT airplanes was approximately 351.4 kilonewtons (79,000 pounds). The F-111A airplane carried fuel in the wings, whereas the F-111 TACT airplane had no provisions for integral wing tanks. At the start of the test maneuvers the F-111A integral wing tanks were empty. At the test conditions, the roll inertia of the F-111 TACT airplane was approximately 30 percent higher than that of the F-111A airplane.

ANALYSIS CONSIDERATIONS

This study was made to evaluate aerodynamic and maneuver performance in conjunction with precision controllability. An overall comparison of the aircraft was made by using the agility assessment technique described in reference 1. Some data are presented in coefficient form based on the appropriate wing area for each airplane at the 16° wing-sweep position. For the F-111A airplane, the reference wing area is 48.75 square meters (524.7 square feet); for the F-111 TACT airplane, the reference wing area is 56.10 square meters (603.9 square feet). The data in coefficient form were used primarily to compare the aerodynamics of each airplane and to evaluate the effects of wing-sweep position. The overall performance comparison (the agility assessment) of the two aircraft is made in terms of normal acceleration. For this comparison, the data were adjusted to 289.1 kilonewtons (65,000 pounds) of gross weight (the approximate combat gross weight for the F-111A airplane) because it was felt that the most meaningful agility comparison would be one based on a common combat gross weight. However, this assumes that an F-111 TACT production airplane could be constructed for the same combat gross weight as the F-111A airplane. It should be noted that some differences in the trends may be observed in the data between the coefficient presentation (disciplinary sections) and the a_n presentation in the agility section. This is largely due to the greater wing area (lower wing loading) of the F-111 TACT airplane as compared with the F-111A airplane. The data shown as a function of a_n indicate the overall performance realized by the pilot. Appendixes A, B, and C discuss the analysis techniques used and the scope of the evaluation of the aircrafts' aerodynamic performance, maneuver performance, and precision controllability, respectively.

For this report, subsonic Mach numbers refer to Mach numbers of 0.75 and less; transonic Mach numbers refer to Mach numbers greater than 0.75 and less than 1.00.

RESULTS AND DISCUSSION

Vehicle Characteristics

The F-111A and F-111 TACT airplanes, like most fighter aircraft during maneuvering flight at transonic speeds, are subject to handling qualities deficiencies which are often initiated by wing flow separation. At these conditions, the effects of the separated flow inhibit and often prevent full use of the maneuvering potential of the aircraft. Another factor which must be considered is the proper blending of the aerodynamic configuration and the control systems. Inadequate blending of these elements is often detrimental to pilot control and can cause handling qualities difficulties at all angles of attack. This section of the report gives a general description of the handling qualities deficiencies that characterized both aircraft; the supercritical wing caused some differences between the aircraft, and these differences are described in later sections.

Figures 5 and 6 present windup turn time histories for the F-111 TACT and F-111A aircraft, respectively. The windup turn in figure 5, for the F-111 TACT aircraft, was initiated at a Mach number of 0.88. The wings were in the 26° wing-sweep position. The first significant effect of the increasing angle of attack in the windup turn is buffet intensity rise, which usually indicates the beginning of handling qualities difficulties due to wing flow separation. In this particular windup turn, the wingtip accelerometer trace shows buffet intensity rise to occur at a time of approximately 10 seconds. (Appendix A discusses buffet intensity rise and the determination of the buffet intensity rise boundary.) Wing rock onset, which is identified by oscillations in the roll rate trace, occurs at a time of approximately 18 seconds. The pilot made few lateral control inputs during the windup turn; the variations in the aileron trace (deflection of the rolling tail, δ_a) are due to the attempts of the lateral augmentation system to reduce the magnitude of the roll rate produced by the wing rock. The wing rock also produces yaw excursions through aerodynamic lateral-directional coupling, and this results in the moderate sideslip excursions shown in the figure. The rolling and yawing motions resulting from the wing rock significantly degrade airplane handling qualities. In addition, the severe drag penalties associated with wing flow separation (denoted by the significant increase in wingtip acceleration starting at a time of 19 seconds) degrade the aircraft's maneuver performance.

Both aircraft exhibited adverse yaw throughout the flight envelope, particularly at low speeds; a lateral control sensitivity that often produced a lateral pilot-induced oscillation (PIO) tendency when high-gain control activity was required; and a reduction in pitch stability for the forward wing-sweep positions in the angle of attack range from 9° to 11°. The adverse yaw was due to the tendency of the aircraft to roll about its principal axis, which produced yaw by trading angle of attack for sideslip. (Both the spoilers and the differential tail produced proverse or favorable yaw.) The lateral control sensitivity, which was attributed to the nonlinearity of the spoiler scheduling, was most noticeable at angles of attack above the buffet intensity rise boundary. The reduction in pitch stability is typical of swept-wing aircraft and is due to wingtip flow separation.

The adverse yaw and lateral control sensitivity are illustrated in the F-111A time history in figure 6. This figure shows a tracking windup turn that was initiated at a Mach number of 0.85 and an altitude of 8.5 kilometers (28,000 feet) with the 26° wing-sweep position. The first half of this time history shows increased aileron stick motion and airplane motion as compared with the smooth windup turn maneuver in figure 5. Adverse yaw spikes are the dominant feature of the latter portion of this maneuver.

All of the characteristics described are typical of both aircraft.

Aerodynamic Performance

The buffet characteristics of the F-111A airplane for wing-sweep positions of 26°, 50°, and 72.5° are reported in detail in reference 14. The buffet intensity rise boundaries in reference 14 for the 26° wing-sweep position were similar to those found in this study.

Buffet intensity rise boundaries.—The buffet intensity rise boundaries for the F-111A and F-111 TACT aircraft are shown in figures 7 and 8, respectively, for wing-sweep positions of 26°, 35°, and 58°. The boundaries are shown in terms of airplane normal-force coefficient as a function of Mach number. At the 26° wing-sweep position for the F-111A airplane (fig. 7), the normal-force coefficient for buffet intensity rise tends to decrease rapidly as speed increases from subsonic to transonic flight. At high transonic speeds, the boundary rises slightly as supersonic flow is approached. The boundary for the 35° wing-sweep position is similar to that for the 26° wing-sweep position; however, the boundary is lower at subsonic speeds and is slightly improved at intermediate transonic speeds. At the 58° wing-sweep position, the boundary does not change as Mach number increases, and it is at a generally lower level for most of the Mach numbers tested.

The variations in the boundary for the F-111 TACT airplane are shown in figure 8. The boundaries do not change significantly as Mach number increases except at high transonic speeds for the 26° and 35° wing-sweep configurations. For both of these configurations, the boundary rises rapidly at a Mach number of approximately 0.92, that is, as supersonic speeds are approached.

Figure 9 summarizes the boundaries for the three wing-sweep positions for each airplane. For the F-111A airplane, the effects of Mach number are rather pronounced and indicate that the optimum wing-sweep position is 26° for subsonic speeds and 35° at intermediate transonic speeds. Both the 35° and 58° wing-sweep positions are better than the 26° wing-sweep position at high transonic speeds. It should be noted that although the more forward wing-sweep position shows a higher buffet intensity rise boundary than the 58° position at Mach numbers approaching 1.0, the intensity characteristics at higher normal-force coefficients for the 58° wing-sweep position are less severe. These effects are discussed in the next section.

The results for the F-111 TACT airplane indicate the highest boundary for the 26° wing-sweep position. At transonic speeds, all the F-111 TACT boundaries are higher than the F-111A boundaries. However, at lower subsonic speeds the F-111A airplane has a somewhat higher buffet intensity rise boundary than the F-111 TACT airplane.

Normal-force and buffet intensity characteristics.—The normal-force and buffet intensity characteristics of both test aircraft are shown in figure 10 for selected wing-sweep positions at a Mach number of approximately 0.88. The normal-force-versus-angle-of-attack curves for the F-111A airplane exhibit differences in slope for the wing-sweep positions shown, as would be expected. Some differences are also apparent in the airplane's buffet intensity characteristics with different wing positions. With the 26° wing-sweep position, the buffet intensity does not have a well defined intensity rise when compared with the data for higher wing-sweep positions. Instead, there is a gradual buffet intensity rise at $C_{N_A} = 0.20$ and a more pronounced one at $C_{N_A} = 0.60$. The first buffet intensity rise is the one represented in figure 9. At this Mach number, there is definitely a residual level of wing flow separation at the lower C_{N_A} for buffet intensity rise. (See appendix A for additional discussion.)

At the higher normal-force coefficients, the buffet intensity rise characteristics for the 58° wing-sweep position indicate lower intensity levels than shown for the more forward wing-sweep positions.

The F-111 TACT data indicate that there are differences similar to those for the F-111A airplane in the normal-force-versus-angle-of-attack curves for the wing-sweep positions shown. However, buffet intensity rise occurs at a much higher normal-force coefficient in the F-111 TACT airplane with the 26° wing-sweep position than in the F-111A airplane. The buffet intensity levels at high normal-force coefficients are considered moderate. The normal-force and buffet intensity characteristics for other Mach numbers and wing-sweep positions are summarized in appendix A.

Wing rock onset.—Wing rock may be defined as an irregular and uncommanded rolling-yawing motion that prevents precise control. Wing rock onset, like buffet intensity rise, is a phenomenon of flow separation. Figure 5, which was discussed in a previous section, illustrates wing rock and its effect on airplane response in roll and yaw. Figure 11 shows the wing rock boundaries for both airplanes for the 26° and 35° wing-sweep positions as determined from the roll rate traces of smooth windup turn time histories (for example, fig. 5). No wing rock was encountered with the 58° wing-sweep position. The wing rock boundaries for the F-111A airplane change somewhat as speed increases from subsonic to transonic. For the F-111 TACT airplane, the normal-force coefficients for wing rock onset increase slightly with increasing Mach number. At transonic speeds, the improvement in the boundary for the F-111 TACT airplane at $\Lambda = 26°$ is significant when compared with that for the F-111A airplane.

Maneuver Performance

Level acceleration performance.—Energy-maneuverability data for wing-sweep positions of 26° and 58° were obtained from 1g level accelerations at an altitude of 9.14 kilometers (30,000 feet). The 26° wing-sweep data for the F-111 TACT aircraft ranged in Mach number from 0.60 to 0.95; since the 26° wing-sweep data for the F-111A airplane were limited to Mach numbers from 0.68 to 0.72, these data were supplemented by F-111A flight test results from reference 15. The 58° wing-sweep data for both aircraft ranged in Mach number from 0.70 to 1.60.

The level acceleration performance for the F-111A and F-111 TACT aircraft are summarized in terms of specific excess power, p_s, in figure 12. The variations in the 1g instantaneous specific excess power with Mach number show the transonic drag rise at the 26° and 58° wing-sweep positions as well as the supersonic acceleration capability for the 58° wing-sweep position. At the 26° wing-sweep position, the supercritical wing raises the drag-rise Mach number from Mach 0.80 to Mach 0.90 and improves the aircraft's transonic acceleration capability. The improvement in drag-rise Mach number is also apparent in the wind-tunnel data presented in appendix B. The supercritical wing did not raise the drag-rise Mach number at the 58° wing-sweep position; in fact, the supercritical wing caused a slight penalty in specific excess power at low supersonic speeds. However, the supercritical wing did not degrade the supersonic acceleration capability of the aircraft at this wing-sweep position.

Sustained turn performance.—The variation of normal-force coefficient for a maximum sustained turn, $C_{N_{A_{p_s=0}}}$, summarizes energy-maneuverability data obtained at constant Mach number/constant throttle conditions. Data were obtained for both the F-111A and F-111 TACT airplanes at the 26°, 35°, and 58° wing-sweep positions. The sustained turn performance summary is based primarily on energy-maneuverability data obtained at a dynamic pressure of 14.4 kN/m^2 (300 lb/ft^2); however, data were also obtained at dynamic pressures of 10.5 kN/m^2 (220 lb/ft^2), 21.6 kN/m^2 (450 lb/ft^2), and 38.3 kN/m^2 (800 lb/ft^2). All energy-maneuverability data presented herein are fairings of the flight test results summarized in appendix B.

Figures 13(a) and 13(b) summarize the effects of Mach number and wing-sweep position on the maximum sustained turn capability of the F-111A and F-111 TACT aircraft, respectively. Maximum sustained turn capability is shown in terms of the normal-force coefficient at zero specific excess power, $C_{N_{A_{p_s=0}}}$.

At subsonic speeds, the sustained turn performance for both aircraft is best with the forward wing-sweep positions. Mach number effects are encountered at a lower Mach number with the F-111A airplane. This is largely attributed to the lower drag-rise Mach number for the F-111A airplane. (As discussed in appendix B, the drag-rise Mach number varies from Mach 0.68 to Mach 0.80 for the basic (F-111D) airplane and from Mach 0.80 to Mach 0.88 for the F-111 TACT airplane over the normal-force-coefficient range.) The sustained turn performance of the F-111A airplane is improved by increasing the wing sweep from 26° to 35° at Mach 0.80. The benefits of increasing wing sweep are delayed to Mach 0.88 for the F-111 TACT airplane. At higher transonic speeds, the data indicate that the 58° wing-sweep position may provide higher sustained turn performance for both airplanes.

PRECISION CONTROLLABILITY

The tailchase tracking technique used to assess precision controllability is discussed in reference 4 and summarized in appendix C.

All the tracking runs for both aircraft in which no handling qualities deficiencies occurred are summarized in figure 14. Figure 14(a) presents the F-111A data and shows tracking precision to be essentially independent of Mach number and wing-sweep position. The root-mean-square (rms) tracking error, approximately 4.5 mils, compares favorably with the level established in an earlier F-111A flight program that utilized a constant-g tracking maneuver (ref. 4). The F-111 TACT tracking data (fig. 14(b)) are similar to those for the F-111A airplane, with somewhat more scatter.

Three handling qualities deficiencies that degraded tracking precision—adverse yaw, lateral control sensitivity, and wing rock—were described in an earlier section

of this report. While none of these deficiencies is peculiar to the supercritical wing, adverse yaw appeared to be slightly greater and lateral control less sensitive with the F-111 TACT airplane. One explanation may be the difference in the spoiler effectiveness between the two configurations. Unpublished wind-tunnel data indicate lower spoiler effectiveness for the F-111 TACT airplane at the lower angles of attack. Both deficiencies caused similar amounts of degradation in tracking accuracy, primarily in the yaw or azimuth plane, and both deficiencies were more pronounced at the lower normal-force coefficients (angles of attack). Wing rock was found in both the F-111A and F-111 TACT aircraft at the forward wing-sweep positions, at the lower subsonic Mach numbers for the F-111A airplane and at the higher subsonic and transonic Mach numbers for the F-111 TACT airplane. This deficiency, which has been found to some degree in all fighter aircraft investigated to date, has less effect on the F-111A and F-111 TACT aircraft than most other fighters. This is attributed to the fact that the F-111A and F-111 TACT configurations have relatively large inertia in roll for fighter aircraft, use rolling tails that are relatively unaffected by wing flow separation, and incorporate high-gain stability augmentation systems.

Figure 15 illustrates the effect of the F-111A/F-111 TACT lateral stability augmentation system on wing rock. Figure 15(a) identifies the character of the wing rock that occurs during a smooth windup turn with the stability augmentation system on. Wing rock onset occurs at a time of 9.5 seconds and may be classified as moderate (ref. 1 gives a description of wing rock magnitudes). As in the windup turn in figure 5, this maneuver shows few lateral control inputs by the pilot but considerable activity in the aileron trace (deflection of the rolling tail). Figure 15(b) illustrates a windup turn time history for approximately the same flight conditions with the roll augmentation system turned off for demonstration purposes. The roll rate trace indicates that wing rock onset (t = 1.5 sec) occurs at a lower buffet intensity than in the maneuver shown in figure 15(a). This suggests that the roll augmentation system is beneficial in delaying wing rock onset. It may also be noted that in the augmentation-off maneuver the roll rate and sideslip excursions associated with the wing rock are greater than in the augmentation-on maneuver.

This investigation also revealed that the wing rock boundaries established in smooth maneuvers were not necessarily valid for more abruptly executed maneuvers. An analysis of smooth windup turns (fig. 11) indicated the F-111 TACT airplane to have higher wing rock onset boundaries than the F-111A airplane. At Mach 0.88 and with the 26° wing-sweep position, the gain in C_{N_A} for wing rock onset was approximately 0.12. Although the data are meager, the wing rock onset boundaries established from the tailchase tracking maneuvers indicate that the gain in $C_{N_{A_{wro}}}$ for the F-111 TACT airplane is limited. Figure 16(a) shows that the F-111A boundary obtained from smooth windup turn maneuvers (fig. 11) agrees with the data obtained from the tailchase tracking maneuvers. Figure 16(b) indicates that the F-111 TACT boundary obtained from smooth maneuvers lies above the data obtained from tailchase tracking maneuvers with the 26° wing-sweep position at transonic speeds. Small spoiler deflections, which are frequent during the tracking task, are suspected of causing the lower boundary. Unpublished wing pressure data obtained from this program indicate that there is a strong shock wave at the spoiler chord station at the

higher subsonic and transonic Mach numbers at the angles of attack where wing rock onset occurs. It may be that even small spoiler deflections produce significant changes in the wing flow characteristics and thus induce wing rock.

Figure 17 illustrates the effects of adverse yaw and wing rock on precision controllability. This figure presents a time history of an F-111 TACT tracking windup turn to the left at an initial Mach number of 0.88 and a dynamic pressure of 14.4 kN/m^2 (300 lb/ft^2). The attacker pilot established his range in a slight bank to avoid the target aircraft's wake, called the target pilot to start the maneuver, and turned the camera on. Almost immediately, an adverse yaw spike produced a significant tracking error, primarily in the yaw (azimuth) axis (adverse yaw characteristics for both airplanes are discussed in the Vehicle Characteristics section). The tracking after the adverse yaw spike was quite smooth until the onset of wing rock. The wing rock excursions during this maneuver would be classed as mild, with roll rate variations of ±10 degrees per second and sideslip excursions of ±0.5°. Again, the tracking degradation appears primarily in the yaw axis.

Figure 18 summarizes the F-111A and F-111 TACT data for which the handling qualities deficiencies discussed previously were encountered. An analysis of these data indicates that the tracking error is independent of wing-sweep position and Mach number. Figure 18 also indicates that the F-111 TACT data, although showing a bit more scatter, produce essentially the same tracking error as the F-111A data in the presence of handling qualities deficiencies. Compared with many other fighter aircraft, these tracking errors in the presence of adverse yaw and wing rock are small (refs. 1 and 4).

In summary, the addition of the supercritical wing did not significantly change the precision controllability characteristics of the F-111A airplane.

AGILITY ASSESSMENT

The F-111A and F-111 TACT airplanes were compared by utilizing the agility evaluation technique described in reference 1. The technique, which assesses in combination the factors that may be traded to achieve maximum maneuverability or agility, was found to be an excellent method for evaluating overall aircraft maneuverability. These factors include the aircraft's aerodynamic performance, maneuver performance, and precision controllability. Data are presented in terms of normal acceleration for correlation purposes. Where the F-111A and F-111 TACT airplanes were compared on the basis of optimum wing sweep, the choice of wing sweep was based primarily on aerodynamic and maneuver performance. Agility comparisons are made between the F-111A and F-111 TACT airplanes at both subsonic and transonic speeds at selected wing-sweep positions. A subsonic flight condition was chosen for this analysis to make it possible to compare the overall performance of the supercritical wing with a conventional wing at conditions where subsonic flow is predominant and the supercritical wing behaves more like a conventional airfoil. Two of the flight conditions chosen were transonic (Mach 0.80 and Mach 0.88) to illustrate the advantages of the delayed buffet and the improved drag-rise Mach number offered by the supercritical wing. Figure 19 compares the two airplanes at common wing-sweep

positions and shows the advantages offered by the supercritical wing's improved aerodynamics over the Mach number range from 0.70 to 0.88. Figure 20 compares the two airplanes at optimum wing-sweep positions at a common Mach number (Mach 0.88). The data shown in figures 19 and 20 were obtained at a dynamic pressure of 14.4 kN/m^2 (300 lb/ft^2) to permit the airplane to fly at a high enough angle of attack to penetrate the separated flow region yet not exceed its g limits. Figures 21 and 22 compare the F-111A and F-111 TACT aircraft at the F-111 TACT maneuver design point ($M = 0.90$, $h_p = 3048$ m (10,000 ft)). At this condition, flight was at higher g levels and lower angles of attack, and less buffet was experienced, than at the flight conditions in figures 19 and 20.

Figure 19(a) compares the two aircraft for a Mach number of 0.70 and a wing-sweep position of 26°. From the discussion in the previous sections of the report, the 26° wing-sweep position was found to be optimum for both aircraft at this Mach number. At this Mach number, the F-111 TACT airplane is at an off-design maneuver flight condition, regardless of wing sweep. Nevertheless, the F-111 TACT airplane shows a slight improvement over the F-111A airplane in the normal-acceleration-versus-angle-of-attack curves as well as in the normal-acceleration values for buffet intensity rise and sustained turn ($p_s = 0$). There is a slightly greater reduction in slope of the normal-acceleration curve at the higher angles of attack for the F-111A airplane, indicating greater wing flow separation. This is also apparent in the F-111A buffet intensity characteristics. The buffet characteristics indicate lower intensity levels for the F-111 TACT airplane, particularly at the intermediate normal accelerations. As for maneuver performance, the levels of specific excess power are similar at low values of normal acceleration and slightly higher for the F-111 TACT airplane at the sustained turn condition ($p_s = 0$). Wind-tunnel results shown in appendix B indicate that drag rise for the F-111A airplane at this Mach number occurs at $C_{N_A} \approx 0.70$, which corresponds to $a_{n_{cg}} = 1.9$g in figure 19(a), slightly above the buffet intensity rise shown in the figure. The F-111 TACT airplane does not undergo a similar drag increase, which could account for the improvement apparent in figure 19(a) for the F-111 TACT aircraft. The variations in the gunsight tracking miss distances show small differences in the precision controllability characteristics of the two aircraft, indicating that the installation of the supercritical wing caused essentially no change in precision controllability.

The comparisons in figure 19(b) are for a common wing-sweep position of 35° and a Mach number of 0.80. This combination of wing-sweep position and Mach number would be considered optimum for the F-111A airplane and not quite as good for the F-111 TACT airplane. The comparisons indicate a delay in shock-induced flow separation and the resulting drag rise for the F-111 TACT airplane. Significant gains are shown in the normal-acceleration values for the F-111 TACT buffet intensity rise and the condition at $p_s = 0$. The miss distances for this flight condition and wing-sweep position show a slight improvement in the precision controllability characteristics for the F-111 TACT airplane. The spikes in the data for both airplanes can be related to the adverse yaw characteristics of the basic configuration, as discussed previously.

Figure 19(c) compares the airplanes at a common wing-sweep position of 26° at the transonic Mach number of 0.88. At this wing-sweep position, the F-111A airplane is definitely in an off-design configuration, while the F-111 TACT airplane is in its optimum configuration. This comparison is interesting in that it illustrates the aerodynamic improvements afforded by the supercritical wing for a wing-sweep position used in one advanced fixed-wing fighter airplane at a Mach number and altitude combination that is representative of the combat arena for fighter aircraft. The comparison shows the F-111 TACT airplane to be superior in both aerodynamic and maneuver performance, as evidenced by its better buffet and specific excess power characteristics over the entire range of normal-acceleration values shown. The airplane's precision controllability characteristics indicate slightly better tracking for the F-111 TACT airplane. However, both airplanes exhibit a degradation in tracking resulting from adverse yaw and wing rock, with adverse yaw occurring at low levels of normal acceleration and wing rock occurring at the higher normal-acceleration levels. Both adverse yaw and wing rock are less pronounced for the F-111 TACT airplane, as indicated by the difference in the peaks of the tracking miss distance spikes. Wing rock is regarded as moderate for both aircraft and occurs at approximately the same value of normal acceleration.

Figure 20 compares the performance of the F-111A and F-111 TACT aircraft at their optimum wing-sweep positions for a Mach number of 0.88 (58° for the F-111A airplane and 26° for the F-111 TACT airplane). The F-111 TACT data are the same as in figure 19(c). The 58° wing-sweep position was selected as optimum for the F-111A airplane, since the more forward wing-sweep position caused a degradation in aerodynamic performance (higher buffet levels at 1g trim and advanced angles of attack) and, in general, poorer handling qualities. As would be expected, the differences in the aircrafts' agility characteristics are great, partly because of the difference in wing-sweep position. The F-111A airplane has a low buffet intensity rise point, but buffet intensity remains at relatively low levels as normal acceleration increases, which is typical of delta-wing aircraft. The near-delta configuration also has comparatively large drag due to lift, which is also apparent in the maneuver performance data. At low values of normal acceleration the specific excess power values are comparable to those for the F-111 TACT airplane; however, the difference is large at higher values of normal acceleration. The precision controllability comparison indicates only small differences in the aircrafts' tracking error, with both aircraft showing adverse yaw spikes and wing rock. However, the F-111 TACT aircraft shows slightly higher miss distances in the presence of wing rock.

Figure 21 shows a comparison of the airplanes at the F-111 TACT design point ($M = 0.90$, $h_p = 3048$ m (10,000 ft)) for a common wing-sweep position of 58°. This wing-sweep position is not optimum for the F-111 TACT airplane, and it was near the optimum for the F-111A airplane for maneuvering (although this was not verified in flight at this test point). Even though the F-111 TACT airplane is not at its optimum wing-sweep position, the differences in airplane performance are small. The F-111 TACT airplane has slightly higher normal-acceleration values for buffet intensity rise and slightly better sustained turn performance. The precision controllability of the two airplanes is similar except for the adverse yaw spikes in the tracking miss distance for the F-111 TACT airplane.

Figure 22 presents another comparison of the performance of the F-111A and F-111 TACT aircraft at the F-111 TACT design point. As in figure 21, the F-111A airplane is at the 58° wing-sweep position, but the F-111 TACT airplane is in the optimum wing-sweep position of 26°. The change in wing-sweep position affects the F-111 TACT agility characteristics, as would be expected. The level of buffet is low and exhibits no intensity rise for the angle of attack range investigated. The F-111A airplane has better specific excess thrust at low levels of normal acceleration, whereas the F-111 TACT airplane has better sustained turn performance ($p_s = 0$) and better specific excess thrust at the higher normal accelerations. In terms of precision controllability, the miss distances for the two airplanes are similar.

A review of the agility assessment and the preceding material indicates that at subsonic speeds, only small differences are noted in the buffet characteristics, maneuver performance, and precision controllability of the F-111A and F-111 TACT aircraft. For Mach numbers from 0.75 to 0.95, the F-111 TACT airplane is optimum at the 26° wing-sweep position. The effects of Mach number are not as severe at transonic speeds (less than Mach 0.88) as would be expected for an airplane with a conventional wing. The F-111A maneuverability characteristics are sensitive to changes in Mach number. Increasing the wing sweep improves the aircraft's overall performance at transonic Mach numbers, but, regardless of wing-sweep position, the transonic maneuverability of the F-111A airplane is significantly less than that of the F-111 TACT airplane.

PILOT COMMENTS

Pilot comments have considerable value in assessing the maneuverability of fighter aircraft. A pilot often demands the maximum turn performance of the aircraft, but at the same time he requires the level of control necessary to maneuver the aircraft tactically to meet the tracking requirements of the weapons system. A number of handling qualities deficiencies affect a pilot's opinion of the airplane's maneuverability. The agility technique is designed to assist the pilot in identifying the capabilities and deficiencies of the airplane. The following paragraphs summarize the pilots' comments. Remarks in parentheses were inserted by the authors.

The F-111 TACT flying qualities were similar to those of the F-111A airplane for cruise flight at subsonic speeds. Only small differences were observed for maneuvers performed at low normal accelerations. At higher Mach numbers, where the drag rise was encountered, differences were observed in aircraft agility, however.

During windup turns at subsonic Mach numbers, essentially no differences were observed in the aircrafts' buffet characteristics for the wing-sweep positions tested. Marked differences were observed, however, at high transonic Mach numbers. For the forward and intermediate wing-sweep positions, the F-111A buffet characteristics were extremely sensitive to Mach number. One g buffet was experienced at the 26° wing-sweep position at high transonic speeds at relatively low angles of attack, and increased angles of attack produced higher buffet intensities in the cockpit. (Figure 23, which presents the buffet intensity at the pilot's station

for Mach 0.90 and a wing-sweep position of 26°, indicates a maximum level of approximately 0.6g.) The maximum buffet loads at the cockpit were approximately one-half this value for the F-111 TACT airplane for the same Mach number and wing-sweep position with the same instrumentation. For a given wing-sweep position, the cockpit buffeting for the F-111 TACT airplane was more insensitive to Mach number. In addition, for the more rearward wing-sweep positions, the buffet intensity levels for the F-111 TACT airplane in maneuvering flight were lower than for the F-111A airplane.

Wing rock, which was observed in both aircraft, could generally be described as moderate. It was not nearly as severe in magnitude or frequency as has been experienced in smaller fighter aircraft (ref. 1).

The improvement in the 1g acceleration capability of the F-111 TACT airplane over the F-111A airplane at a wing-sweep position of 26° was significant at transonic speeds. (However, if wing-sweep position were scheduled with Mach number, the 1g acceleration of the F-111A airplane would be similar to that of the F-111 TACT airplane.) At supersonic speeds, the acceleration capability of the aircraft was comparable.

The F-111 TACT airplane was far superior to the F-111A airplane for maneuvering flight at the higher altitudes (9.14 km (30,000 ft) and higher). With the same TF30-P-3 engine, the F-111A sustained turn rates were limited unless large losses in Mach number or altitude were accepted, whereas the F-111 TACT airplane performed the maneuvers with much greater ease.

The F-111 TACT airplane was similar to the F-111A airplane in tracking characteristics in many ways. Both aircraft were somewhat overly sensitive in pitch and roll, although both were well damped. They both had the pitch instability region typical of swept-wing aircraft in the 9° to 11° angle of attack range because of wingtip flow separation. This effect was minor for this investigation, since this angle of attack range was traversed rather quickly in the windup turn tracking maneuvers. At angles of attack below buffet onset, lateral tracking was satisfactory if the target and chase aircraft were satisfactorily positioned before the tracking started. If many initial lateral-directional corrections had to be made that required spoiler extension, however, the resulting response was harsh and abrupt in both aircraft, which led the pilots to tend to overcontrol. In addition, the F-111A airplane exhibited greater lateral looseness in the tracking mission than the F-111 TACT aircraft during heavy buffet. At angles of attack exceeding those for buffet onset, mild to moderate wing rock occurred in both aircraft. This was not particularly bothersome in itself, but the lateral stick activity associated with trying to position the aircraft on the target generated some directional hunting oscillations. These oscillations (although not as severe as those shown in ref. 1) did degrade the tracking task.

CONCLUSIONS

A flight comparison was made of the agility of the F-111A and F-111 TACT airplanes. The flights were made primarily at Mach numbers from 0.70 to 0.95 and at

wing-sweep positions of 26°, 35°, and 58°. The following conclusions were drawn from this investigation:

1. The supercritical wing significantly improved the aircraft's buffet characteristics at transonic speeds. For the forward and intermediate wing-sweep positions, the F-111A buffet boundaries decreased as Mach number increased from subsonic to transonic. The F-111 TACT buffet boundaries did not change significantly until high transonic Mach numbers were reached for these wing-sweep positions, and they were higher than the F-111A boundaries at transonic speeds. The buffet characteristics of the aircraft at the higher normal-force coefficients indicated that the buffet intensity levels for comparable wing-sweep positions were in most cases lower with the F-111 TACT airplane.

2. The maneuver performance evaluation showed that at the 26° wing-sweep position the supercritical wing improved the airplane's drag-rise Mach number and 1g transonic acceleration performance. At the forward and intermediate wing-sweep positions, the supercritical wing was also beneficial in improving the aircraft's transonic sustained turn performance. The 1g acceleration capability of the two aircraft was similar at supersonic speeds.

3. The precision controllability characteristics of the two airplanes were similar at the Mach numbers tested. Each aircraft exhibited adverse yaw throughout the flight envelope which was particularly noticeable at low speeds. Both aircraft experienced moderate wing rock, the F-111 TACT airplane having the higher wing rock onset boundary in smooth windup turns. However, a tracking task that required continuous control inputs indicated that even small deflections of the wing spoilers lowered the wing rock onset boundary from the level determined from smooth windup turns.

4. The pilots commented that the aircraft tracked as well as many current aircraft. However, the buffeting experienced by the pilot in the F-111A airplane was regarded as heavy at transonic speeds for the 26° wing-sweep position. The pilot also experienced greater lateral looseness with the F-111A airplane in the tracking mission during heavy buffet. The higher normal-force coefficient for buffet onset and the lower buffet levels for the F-111 TACT airplane reduced the piloting task in the tracking maneuvers.

5. The agility analysis demonstrated that the 26° wing-sweep position was optimum for both aircraft at low subsonic speeds, with the F-111 TACT airplane slightly better in overall maneuverability. For transonic speeds (Mach numbers from 0.75 to 0.95), the F-111 TACT airplane was again optimum at the 26° wing-sweep position. The F-111A airplane required all three test wing-sweep positions for optimum maneuverability for this Mach number range, and its overall transonic performance was regarded as significantly less than that of the F-111 TACT airplane.

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National Aeronautics and Space Administration
Edwards, Calif., November 1, 1977

APPENDIX A.—AERODYNAMIC PERFORMANCE

Aerodynamic performance was evaluated for this study by assessing the aircrafts' buffet, wing rock, and normal-force characteristics. The buffeting (structural response) data in the study are used as an indicator of wing flow separation. The data were obtained with a digital data acquisition system at 200 samples per second. The accelerometer data were filtered to remove the maneuver component before analysis. The data reduction procedure included an extraneous point removal program, an rms analysis program, and a power spectral density (PSD) analysis program. The fluctuating rms loads were analyzed for continuous 0.5-second time segments during periods of increasing angle of attack during smooth windup turn maneuvers. Computer programs were used to analyze the digital data from the periods chosen for analysis.

Power spectral density techniques were used to indicate the power and the frequency distribution of the buffet parameters. Periods of approximately 3 consecutive seconds were analyzed at times of high buffet intensity and approximately constant angle of attack.

Buffet Intensity Rise Boundary

The buffet intensity rise boundary was defined as the point at which $\bar{\sigma}_{a_{n_{wt}}}$ began to increase rapidly with increasing C_{N_A} (knee of C_{N_A} versus $\bar{\sigma}_{a_{n_{wt}}}$ curve, fig. 24). In general, the pilot detected a buffet intensity change from essentially no buffet to light buffet at subsonic speeds or from a residual level of buffet to a moderate level at transonic speeds. With each increase the pilot noticed a degradation in aircraft performance.

More data were needed than were available from the rms data analyses to describe the buffet boundaries adequately. To supplement the data, the buffet intensity rise boundaries for additional windup turn maneuvers were identified by inspecting time history traces. Figure 24 illustrates the way the buffet intensity rise was determined from the time histories.

Normal-Force and Buffet Intensity Summary

Figures 25 to 28 show data for selected Mach numbers and dynamic pressures for the F-111A and F-111 TACT airplanes. Figures 25 and 27 show the Mach numbers at the beginning of each run. In some cases, Mach number varied as much as 0.05 from the initial condition.

APPENDIX A.—Concluded

Power Spectral Density Characteristics

Figure 29 presents representative PSD analyses of accelerometer data from sensors located in the cockpit and on the wingtip for the F-111 TACT airplane at wing-sweep positions of 26° and 58°. The dashed lines in figure 29(a) indicate the structural modes determined from ground vibration tests conducted by the manufacturer. The agreement between these frequencies and the peaks obtained from the flight data for $\Lambda = 26°$ lends confidence in the instrumentation installation and analysis technique. Ground vibration tests were not conducted at the 58° wing-sweep position. There are some small differences in regard to frequency distribution and power between the $\Lambda = 26°$ and $\Lambda = 58°$ results. Similar power spectral density data for the F-111A airplane are shown in reference 14.

APPENDIX B.—MANEUVER PERFORMANCE

The maneuver performance evaluation in this investigation consists of an assessment of drag-rise Mach number, sustained turn capability, and supersonic acceleration capability. The maneuver performance was evaluated with energy-maneuverablity data obtained from level acceleration maneuvers and accelerating/decelerating turn maneuvers at the flight conditions and wing-sweep positions described in figure 4. The energy-maneuverability data are in terms of specific excess power (p_s) as determined by the data analysis technique described in the appendix of reference 1. The maximum afterburner condition was selected as the most meaningful reference power setting for the execution of the maneuvers. All the p_s data presented for the F-111A and F-111 TACT aircraft are standardized to a reference gross weight of 289.1 kilonewtons (65,000 pounds). In addition, the p_s data are corrected for the effects of nonstandard day temperatures on engine thrust according to the net thrust equation found in the appendix of reference 16. No corrections were made for trim drag effects.

Level Acceleration Performance

Maximum power level accelerations were conducted for the F-111A and F-111 TACT aircraft to evaluate their drag-rise Mach numbers and supersonic acceleration capabilities. A typical level acceleration is shown in figure 30(a) for the F-111A aircraft at a wing-sweep position of 58°. Over the Mach number range shown (0.80 to 1.60), there is unsteadiness in both the trim angle of attack (α) and normal load factor ($a_{n_{cg}}$), causing roughness in the specific excess power calculation. Because of this, only portions of the time history were selected for data analysis. Estimates of p_s obtained from the portions of the time history for which the $a_{n_{cg}}$ trace was either within ±0.05g of 1g or at 1g (shown by the cross-hatched areas and T markings, respectively) are summarized in figure 30(b). This data selection process smoothed the curve and permitted an assessment of the drag-rise Mach number. This analysis procedure was used to arrive at the data in figure 12 for the 26° and 58° wing-sweep positions.

Sustained Turn Performance

Fixed power lever angle accelerating/decelerating turns described in reference 1 were utilized to obtain the energy-maneuverability data that were used to evaluate the sustained turn performance of the F-111A and F-111 TACT aircraft. A time history of a typical maneuver is shown in figure 31(a) for the F-111A airplane at a wing-sweep position of 35° and at a nominal flight condition of $M = 0.70$ and $h_p = 6.86$ kilometers (22,500 feet) for various levels of normal load factor. The throttle was held at the maximum power setting throughout the maneuver. Data analysis was performed for the time segments at the event marks, which correspond

to a common airspeed. The results are numerically identified and presented in figure 31(b) in terms of p_s versus C_{N_A}. The figure shows the maneuverability characteristics from a 1g trim condition to the condition of an effective maximum C_{N_A}. A fairing of the data permits the identification of the normal-force coefficient at $p_s = 0$, that is, $C_{N_{A_{p_s=0}}}$, the condition for a maximum sustained turn, which is of primary interest for a maneuver performance evaluation.

All of the energy-maneuverability data obtained in the transonic Mach number region at the forward, intermediate, and rear wing-sweep positions are presented for the F-111A and F-111 TACT aircraft in figures 32 and 33, respectively. The data are summarized in figure 13.

The rationale for combining the $C_{N_{A_{p_s=0}}}$ from data at various dynamic pressures in figure 13 is presented in figure 34. Figure 34 shows the variation of p_s with C_{N_A} for the F-111 TACT airplane at $M = 0.85$ and dynamic pressures of 14.4 kN/m^2 (300 lb/ft^2) and 21.6 kN/m^2 (450 lb/ft^2). Although the data are limited, $C_{N_{A_{p_s=0}}}$ is nearly the same for both dynamic pressures, even though the effects of dynamic pressure are significant at 1g trim. Energy-maneuverability data from a previous study for two aircraft equipped with turbojet engines also exhibited this characteristic.

Drag-Rise Mach Number

The drag-rise Mach numbers of the conventional and supercritical wings at the 26° wing-sweep position are shown by the wind-tunnel data in figure 35 (ref. 9). The wind-tunnel data were obtained on a 1/24-scale model. The data for both the F-111D and F-111 TACT models were obtained in the NASA Langley Research Center 8-Foot Transonic Wind Tunnel, at unit Reynolds numbers of 18.0×10^6 per meter (5.5×10^6 per foot) for the F-111D model and 21.3×10^6 per meter (6.5×10^6 per foot) for the F-111 TACT model. For the purposes of this report, the aerodynamic characteristics of the F-111D and F-111A aircraft are the same. The difference in the boundaries shows that the supercritical wing is considerably more efficient aerodynamically over the entire normal-force coefficient range. These differences in the boundaries are indicative of the improvements that can be realized in the 1g instantaneous acceleration as well as in maneuver performance at advanced lift coefficients. The effects of the drag-rise Mach number characteristics are evident in the level acceleration and sustained performance data in figures 12 and 13, respectively.

APPENDIX C.—PRECISION CONTROLLABILITY

The degree of precision controllability was established through the use of a constant-range, windup turn tracking maneuver that started in 1g cruise flight and ended when the attacker aircraft reached its limit angle of attack. Runs were performed at subsonic and transonic Mach numbers at a dynamic pressure of 14.4 kN/m^2 (300 lb/ft^2), and at $M = 0.90$ at an altitude of 3048 meters (10,000 feet) (the supercritical wing design point) for three wing-sweep positions. The gunsight was used in the fixed-reticle (caged pipper) mode, with the pipper fixed at a depression angle of 70 mils to minimize the effects of the target aircraft's wake, to keep the pendulum effects inherent in caged pipper tracking constant, and to permit repeatable and comparable data. Thrust was used as required during the tracking runs, but lack of range rate information (a limitation of the caged pipper task) made it difficult for the attacker pilot to maintain range. The pilot was asked to refrain from making rudder inputs during the tracking task to prevent them from masking airplane handling qualities deficiencies. This represented a limitation of sorts, however, since abrupt target aircraft plane changes at advanced load factors invariably produced tracking error spikes. Even with these limitations, this maneuver has been found to produce repeatable and meaningful results in several programs involving both control system and configuration optimization studies. In the present study, it was used to compare the precision controllability of the F-111 TACT and F-111A airplanes.

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TABLE 1.—GEOMETRIC CHARACTERISTICS OF TEST AIRPLANE WINGS

	F-111A airplane	F-111 TACT airplane
Wing		
Airfoil type:		
Pivot	NACA 64A210.7 (modified)	Supercritical
Tip	NACA 64A209.8 (modified)	Supercritical
Span, m (ft):		
$\Lambda = 16°$	19.20 (63.00)	18.08 (59.33)
$\Lambda = 58°$	13.08 (42.93)	11.98 (39.30)
Area, $\Lambda = 16°$, m^2 (ft^2)	48.77 (525)	56.10 (603.9)
Aspect ratio, $\Lambda = 16°$	7.56	5.83
Taper ratio, $\Lambda = 16°$	0.325	0.542
Airfoil thickness ratio, $\Lambda = 16°$, percent:		
W.S. 178.6 (70.3)*	10.68	10.17
W.S. 315.0 (124)*	11.27	9.58
Wingtip	9.8 (theoretical)	5.35 (theoretical)
Leading-edge flap/slat—		
Type	Slat	Krueger
Total area, m^2 (ft^2)	4.5 (48.5) planform projected	5.1 (55.01) stowed
Maximum deflection, deg	45.0	45.0
Trailing-edge flap—		
Type	Double-slotted Fowler	Single-slotted Fowler
Total area, m^2 (ft^2)	10.0 (108.0)	12.5 (135.0)
Maximum deflection, deg	37.5	30.0
Spoilers		
Type	Flap	Flap
Total area, m^2 (ft^2)	2.7 (29.2)	2.5 (26.6)
Maximum deflection, deg	45.0	45.0

*In centimeters (inches).

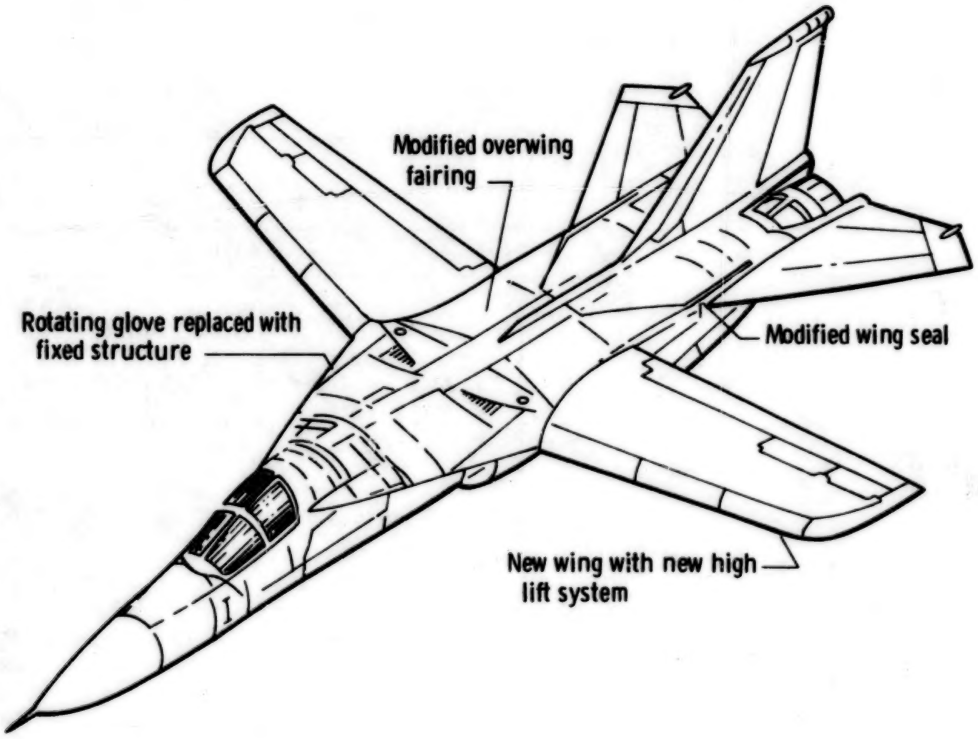
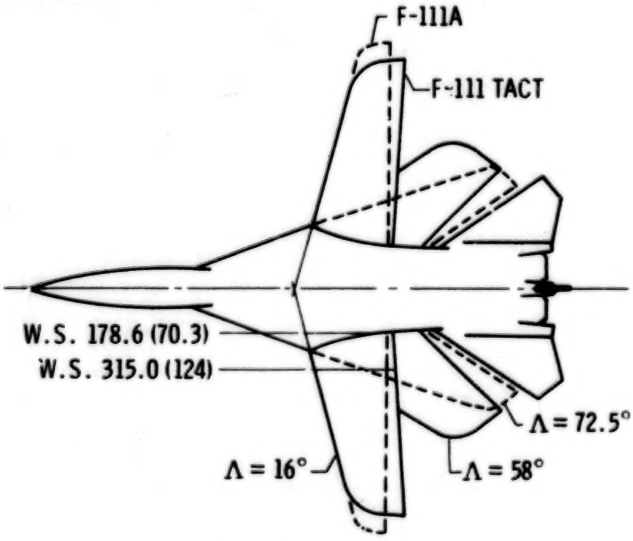

Modified overwing fairing
Rotating glove replaced with fixed structure
Modified wing seal
New wing with new high lift system

Figure 1. Sketch of F-111 TACT airplane indicating airframe modifications.



(a) Aircraft plan views.

(b) F-111 TACT airfoil section at W.S. 315.0 (124.0). t/c = 0.055, AR = 5.83, λ = 0.542.

(c) F-111A airfoil section at W.S. 178.6 (70.3). t/c = 0.098, AR = 7.56, λ = 0.325.

Figure 2. F-111A and F-111 TACT airplane plan views and airfoil section properties at selected wing stations. Wing stations are in centimeters (inches).

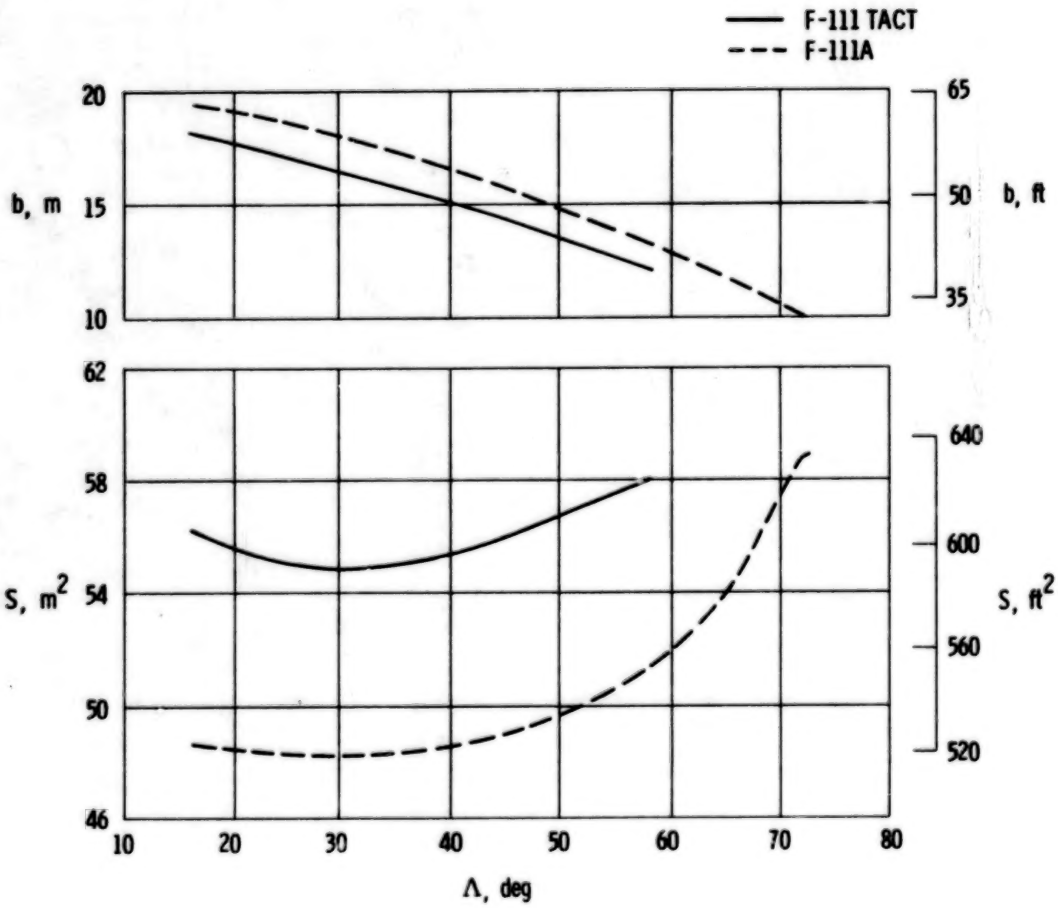


Figure 3. Changes in wing geometry and wing-sweep position for F-111A and F-111 TACT aircraft.

	F-111A	F-111 TACT
	Leading-edge wing sweep, deg	
A	26	26
B	35	35
C	26, 58	26
D	58	26, 58

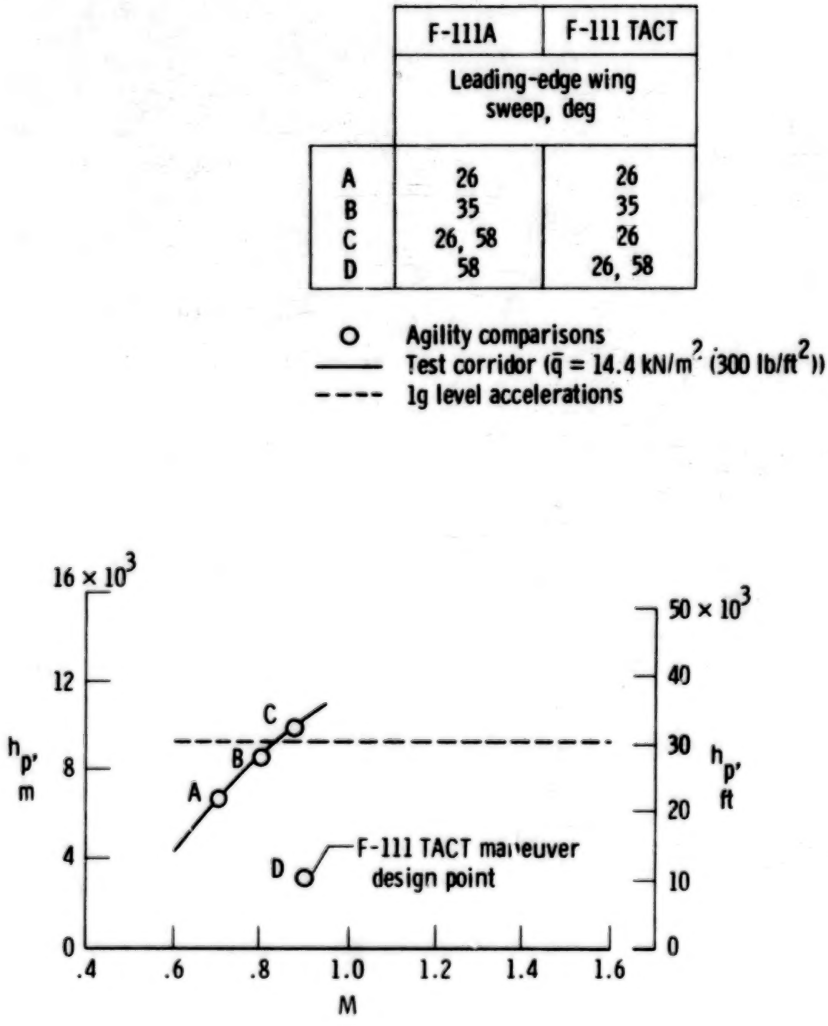


Figure 4. Flight test conditions for F-111A and F-111 TACT aircraft.

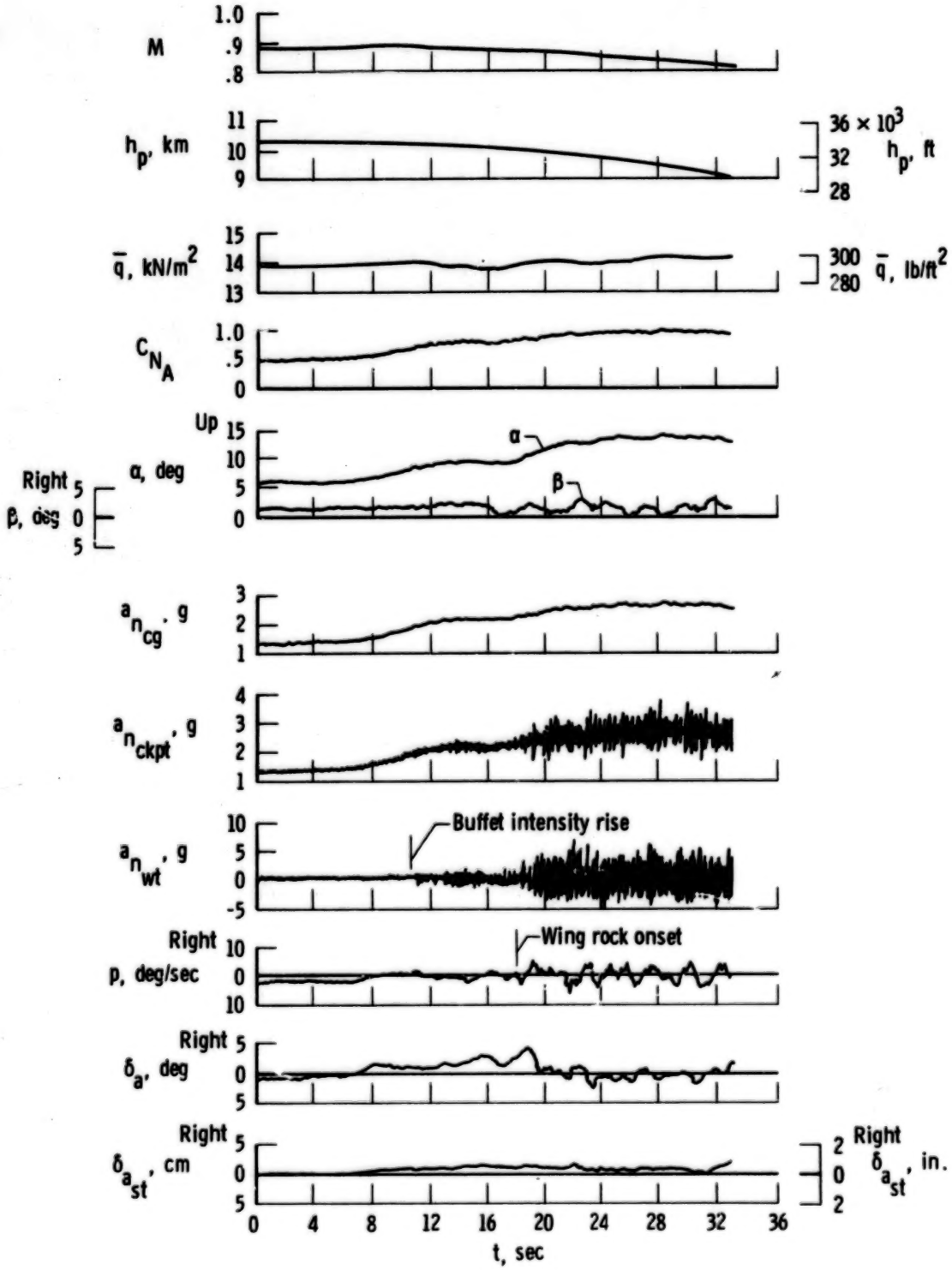


Figure 5. Time history of smooth windup turn illustrating flow separation at higher angles of attack. F-111 TACT airplane; $\Lambda = 26°$.

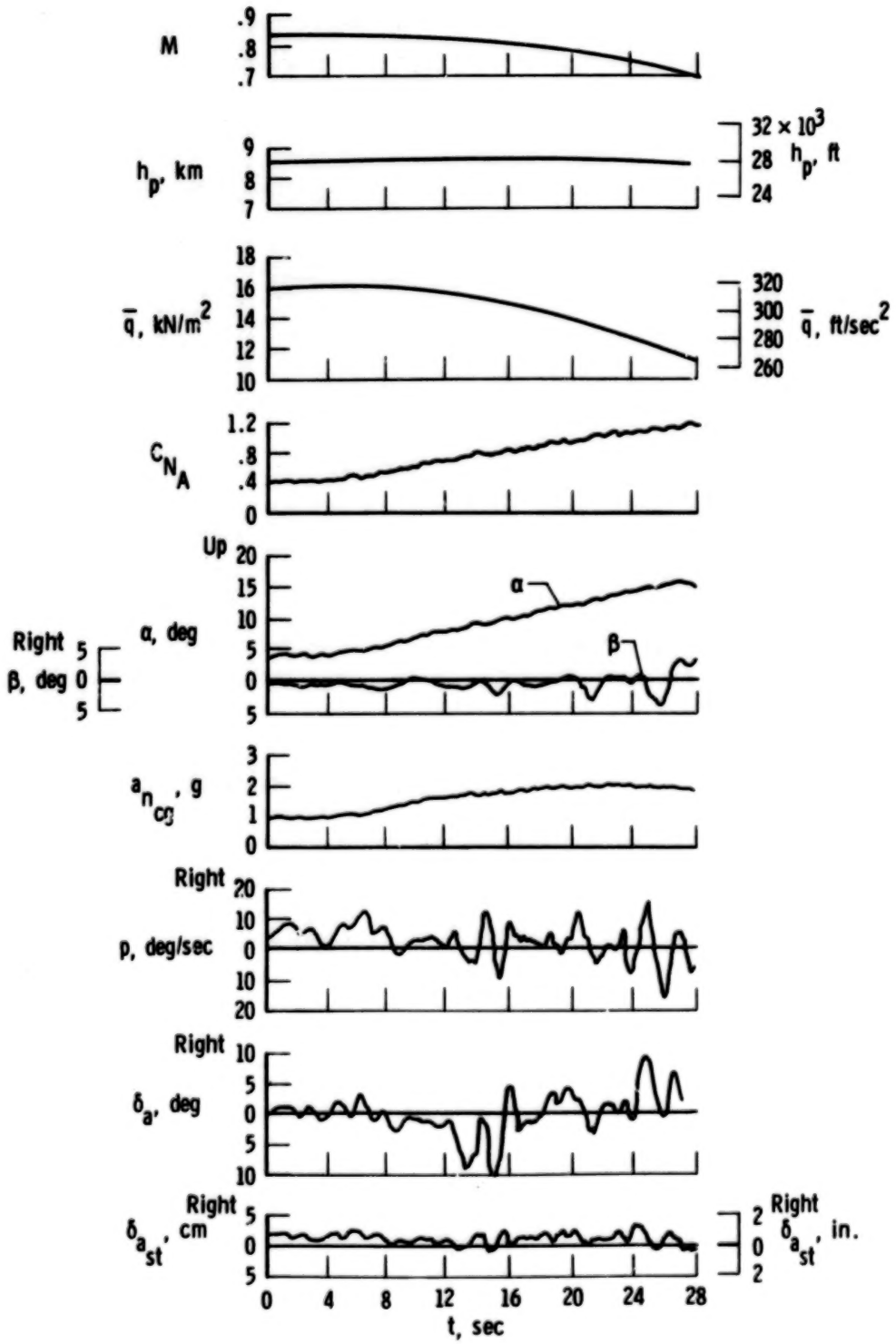
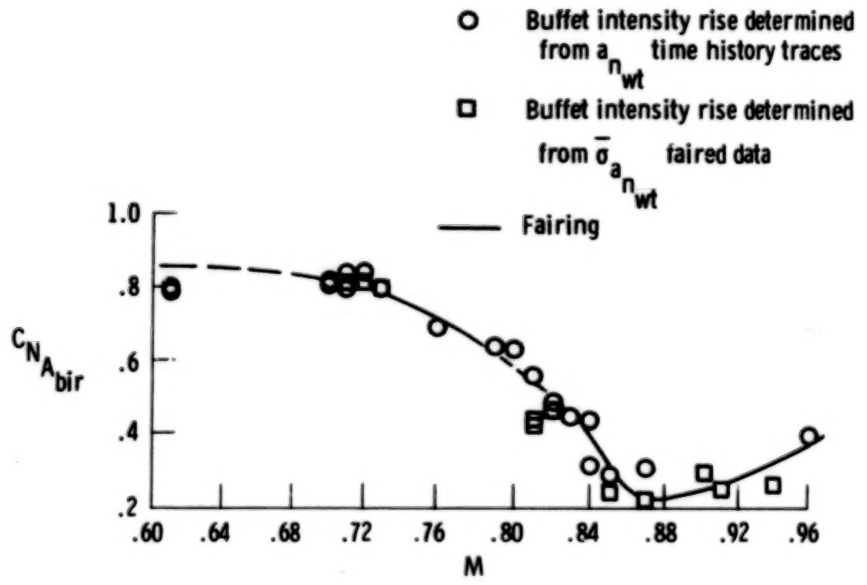
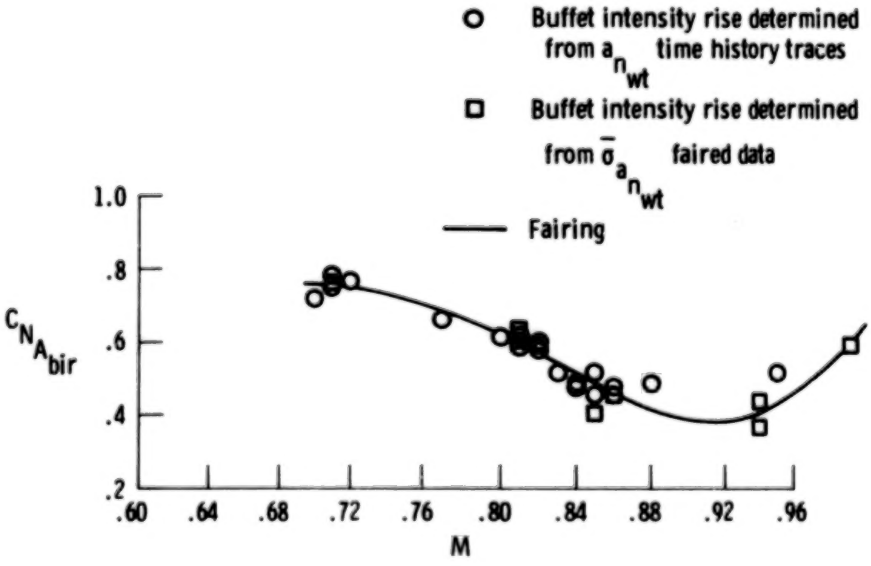


Figure 6. Time history of tracking windup turn illustrating lateral control sensitivity and adverse yaw. F-111A airplane; $\Lambda = 26°$.

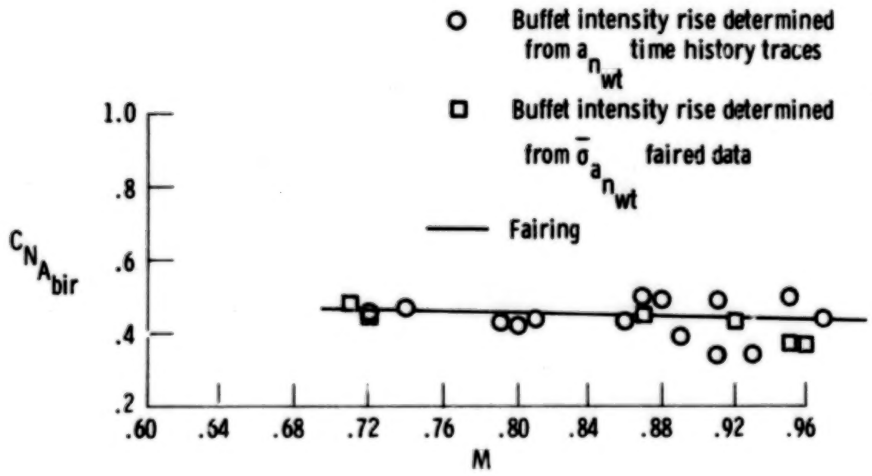


(a) $\Lambda = 26°$.



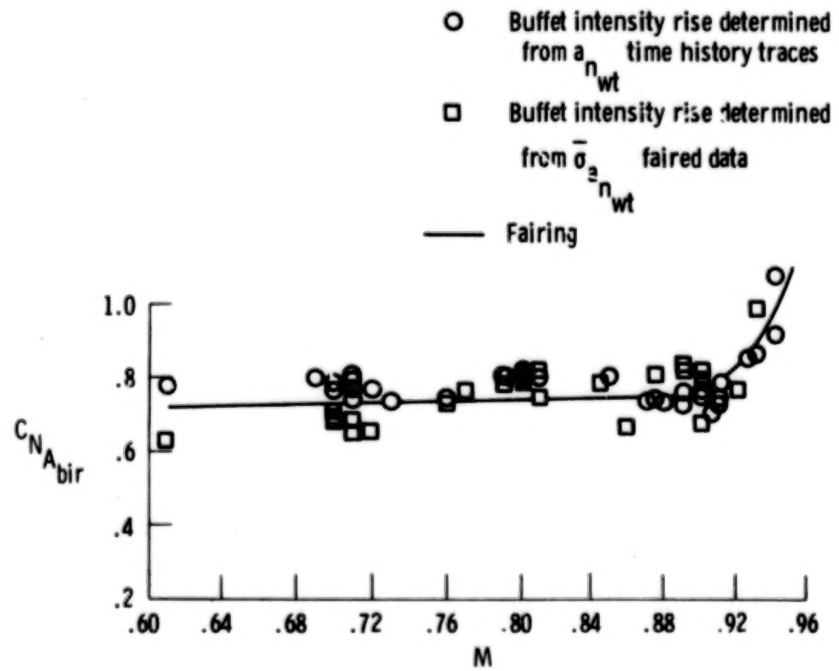
(b) $\Lambda = 35°$.

Figure 7. F-111A buffet intensity rise boundaries.



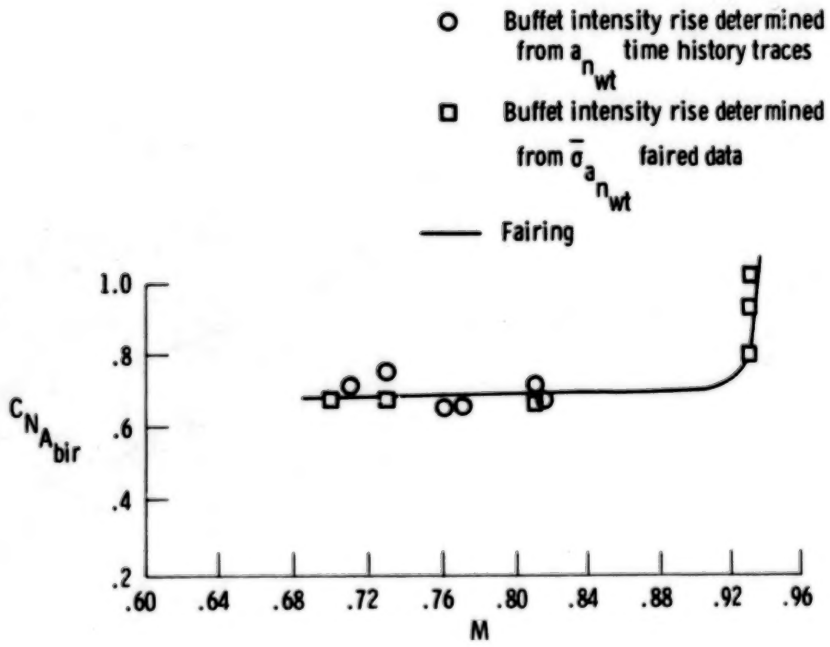
(c) Λ = 58°.

Figure 7. Concluded.

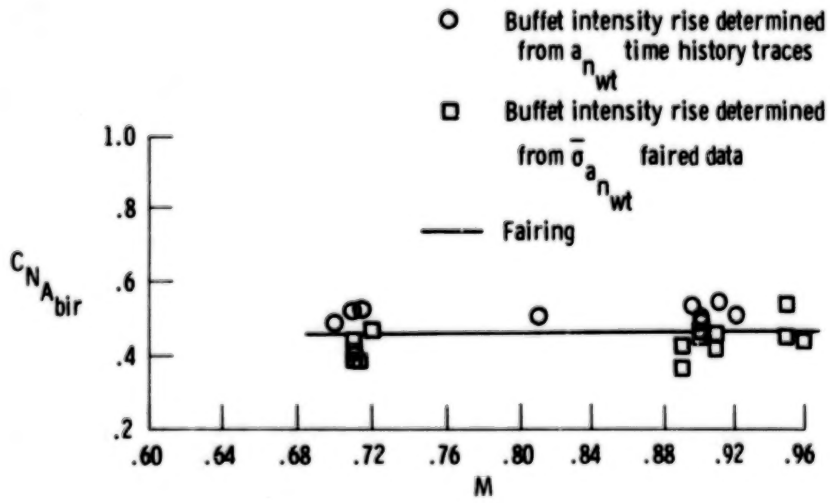


(a) Λ = 26°.

Figure 8. F-111 TACT buffet intensity rise boundaries.

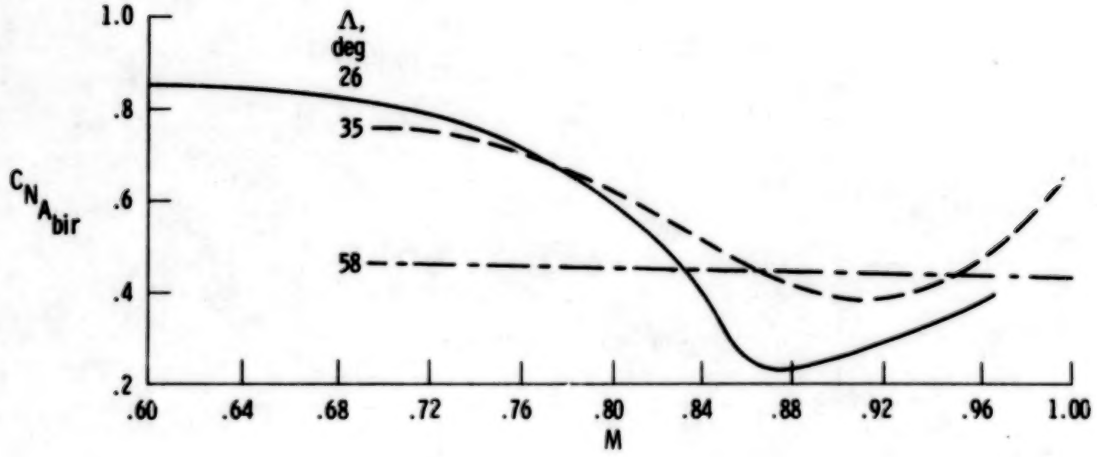


(b) $\Lambda = 35°$.

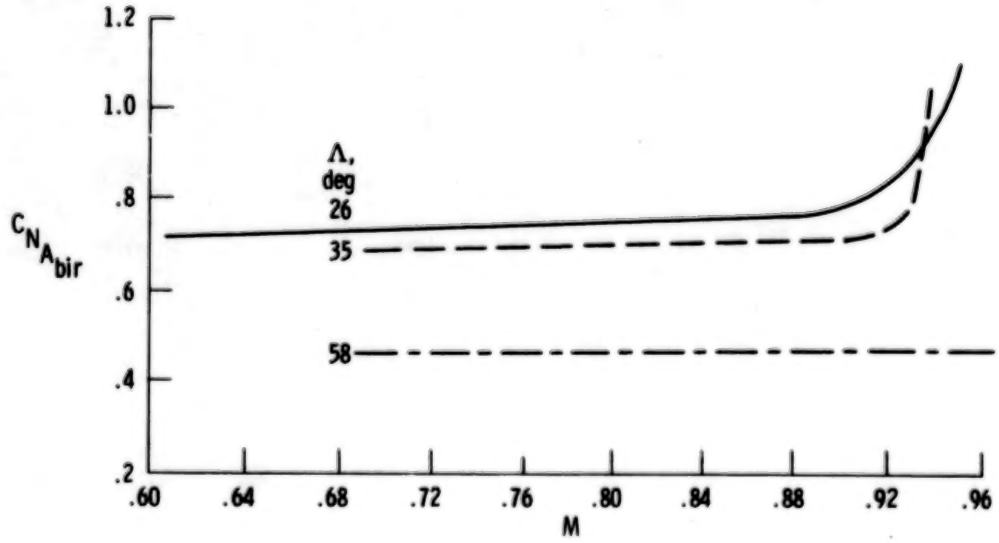


(c) $\Lambda = 58°$.

Figure 8. Concluded.

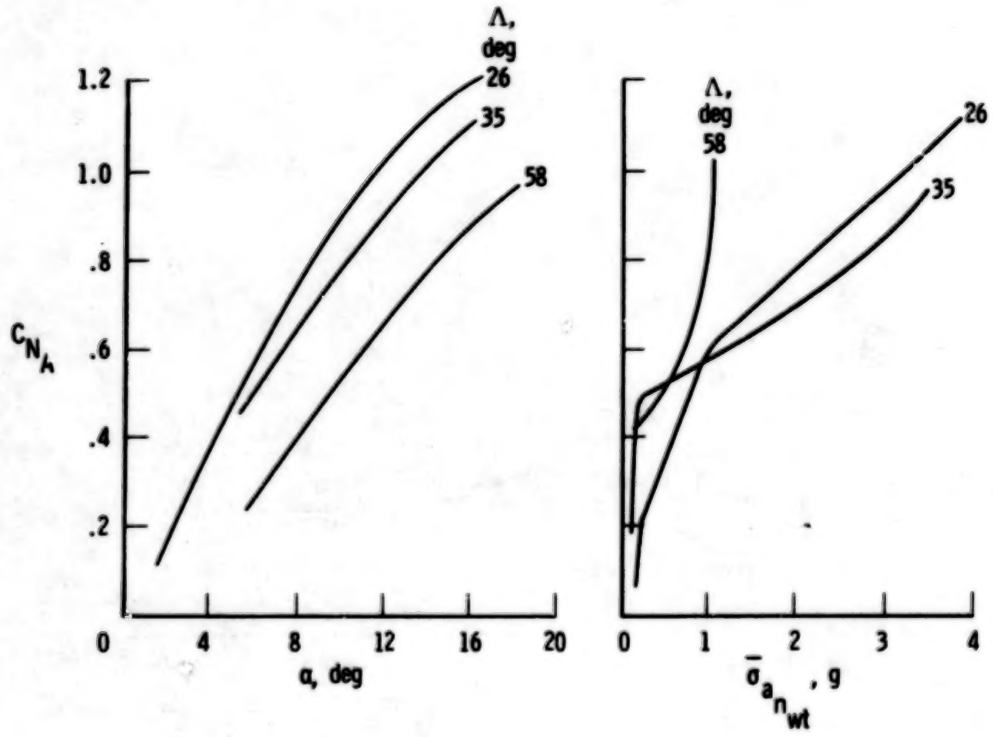


(a) F-111A airplane.

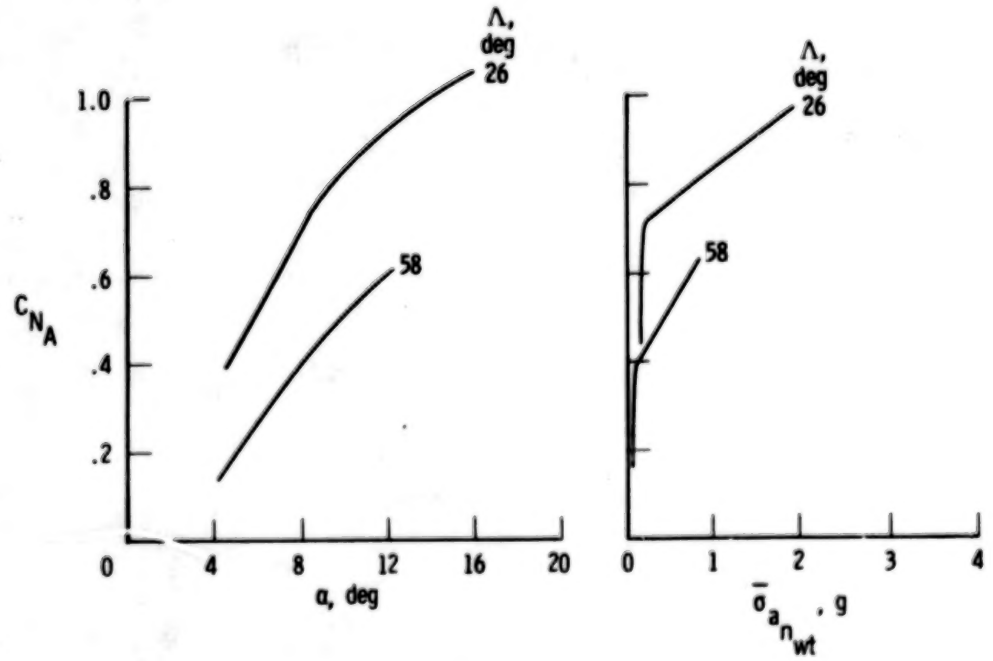


(b) F-111 TACT airplane.

Figure 9. F-111A and F-111 TACT buffet intensity rise summary.

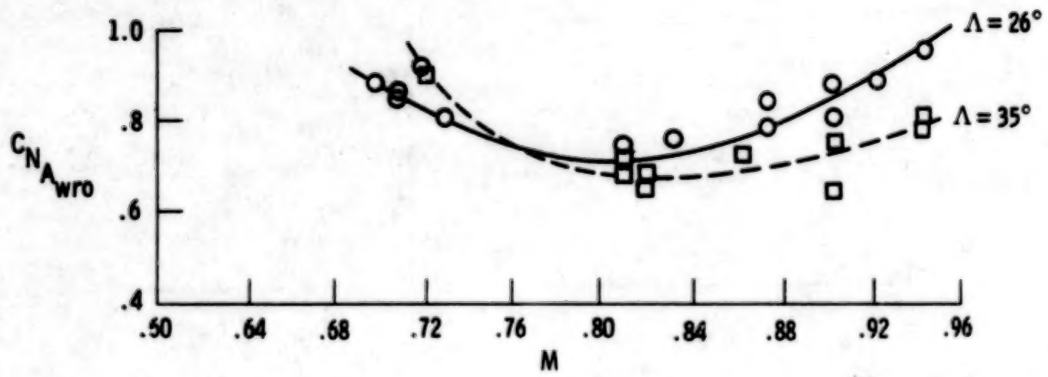


(a) F-111A airplane.

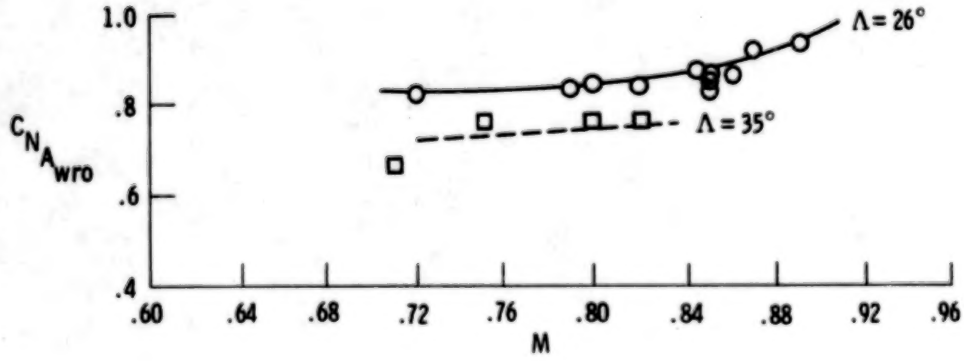


(b) F-111 TACT airplane.

Figure 10. Variation of airplane normal-force coefficient with angle of attack and buffet intensity at selected wing-sweep positions. M = 0.88.

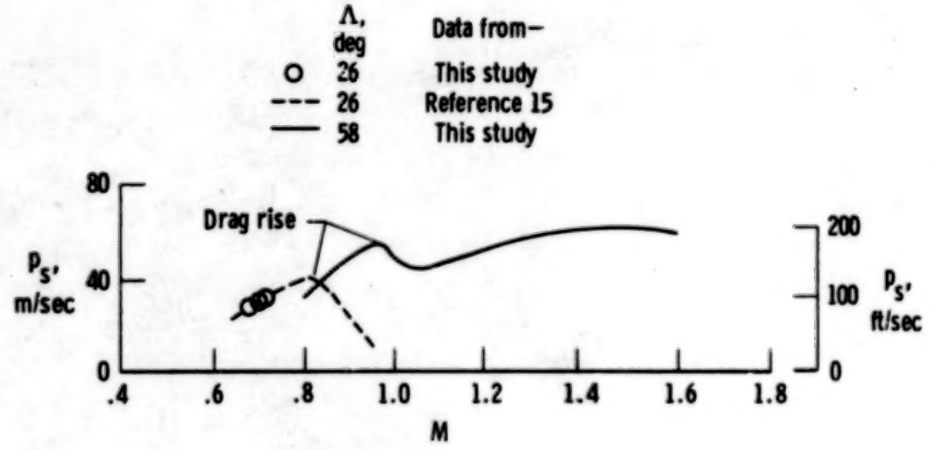


(a) F-111A airplane.

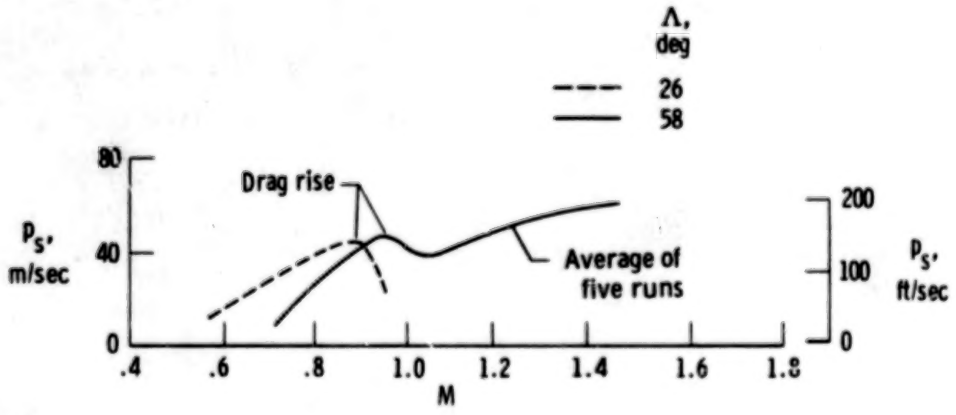


(b) F-111 TACT airplane.

Figure 11. F-111A and F-111 TACT wing rock onset.

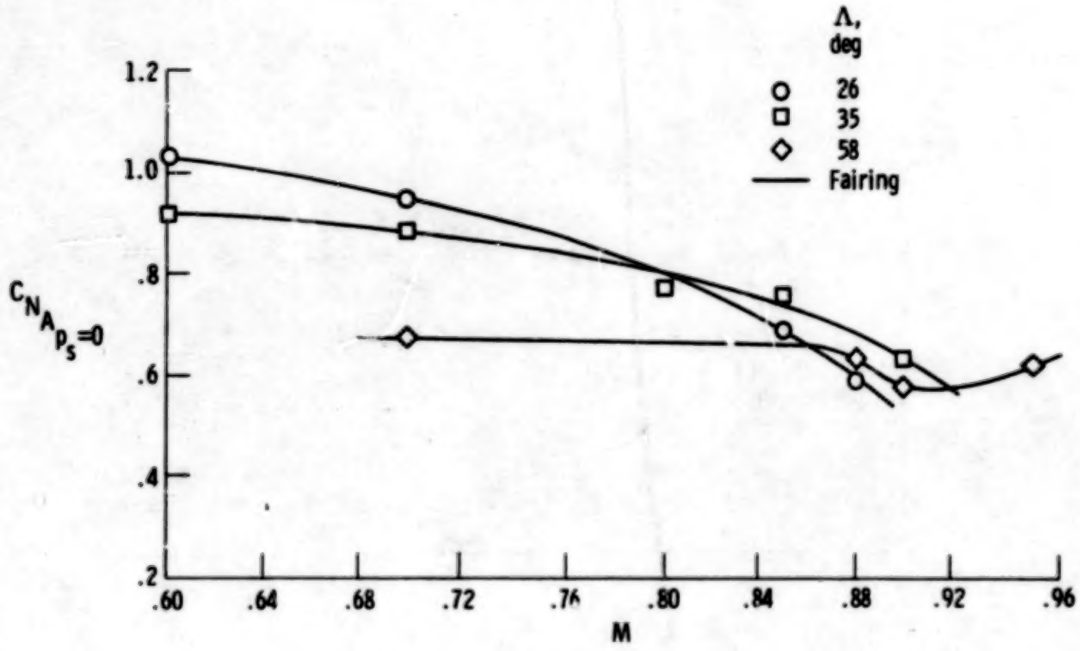


(a) F-111A airplane.

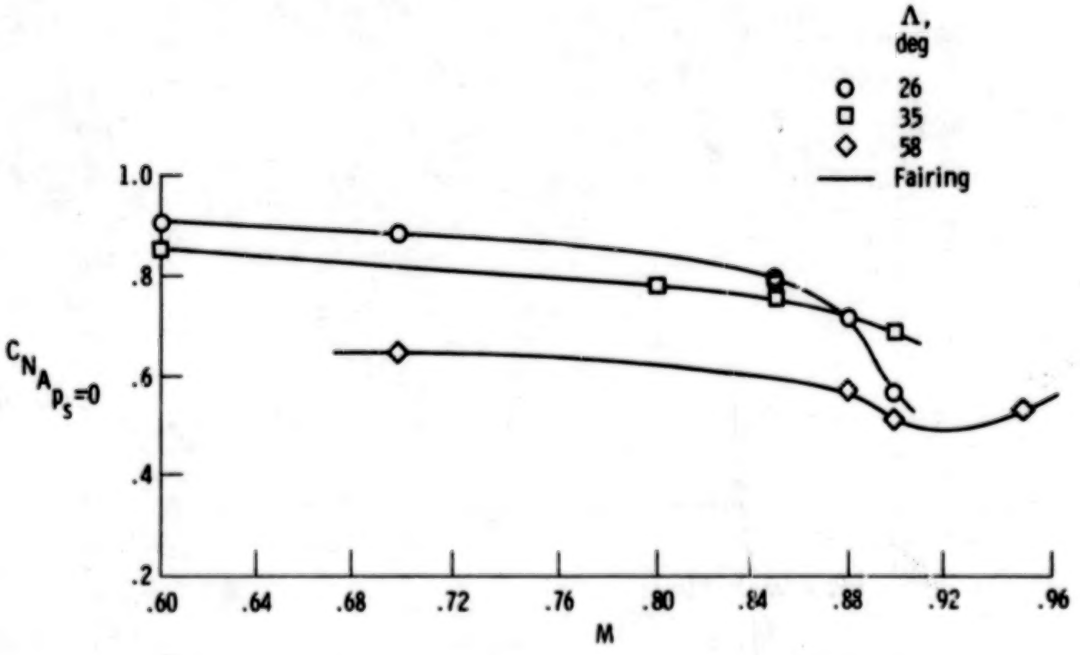


(b) F-111 TACT airplane. All data from this study.

Figure 12. Comparison of 1g specific excess power for F-111A and F-111 TACT aircraft at h_p = 9.14 km (30,000 ft). W = 289.1 kN (65,000 lb).

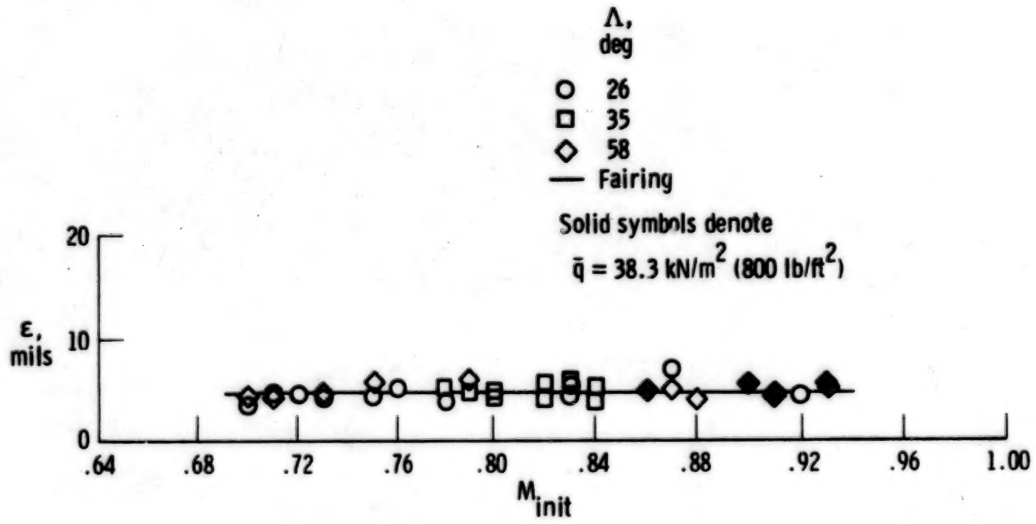


(a) F-111A airplane.

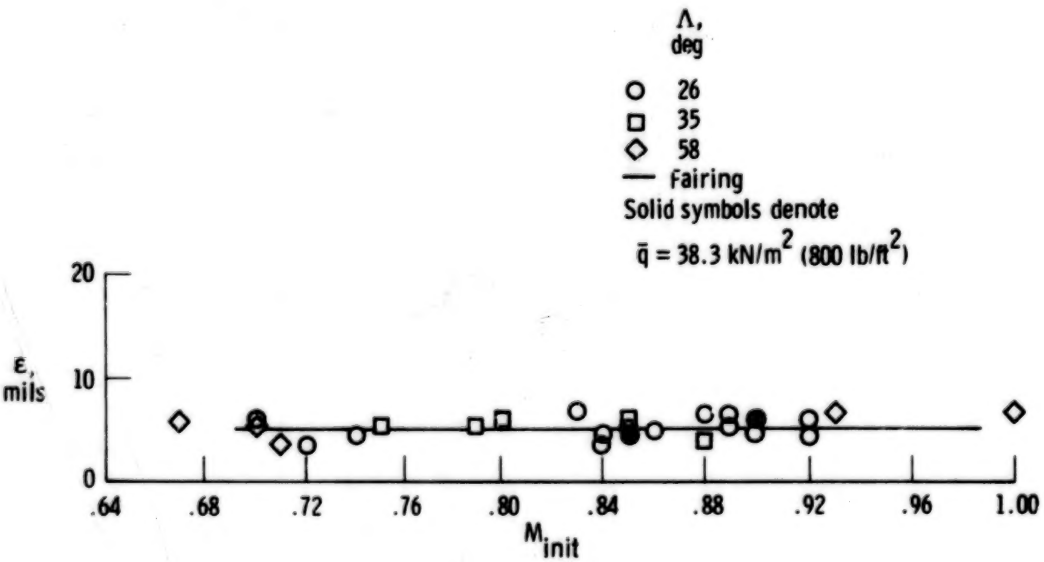


(b) F-111 TACT airplane.

Figure 13. F-111A and F-111 TACT maximum thrust sustained turn performance.

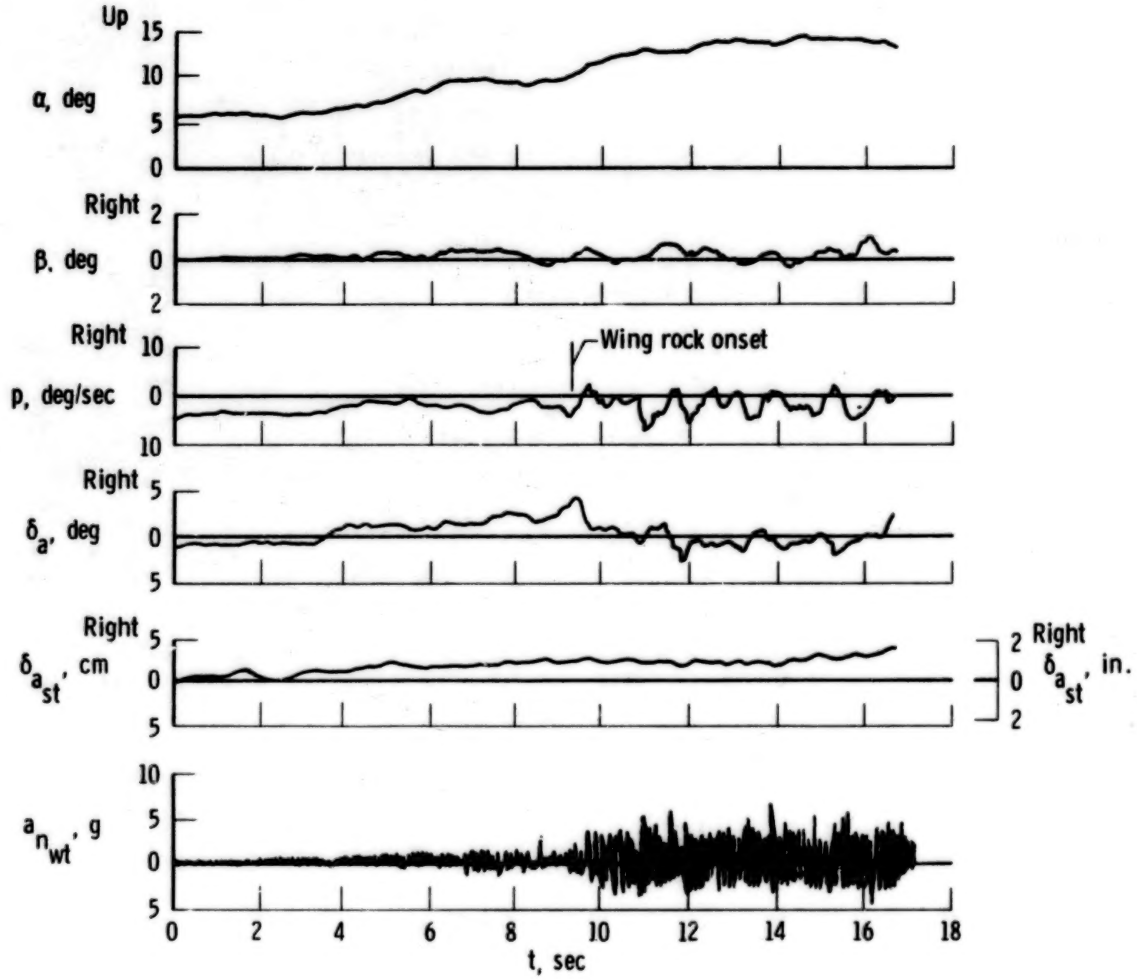


(a) F-111A airplane.



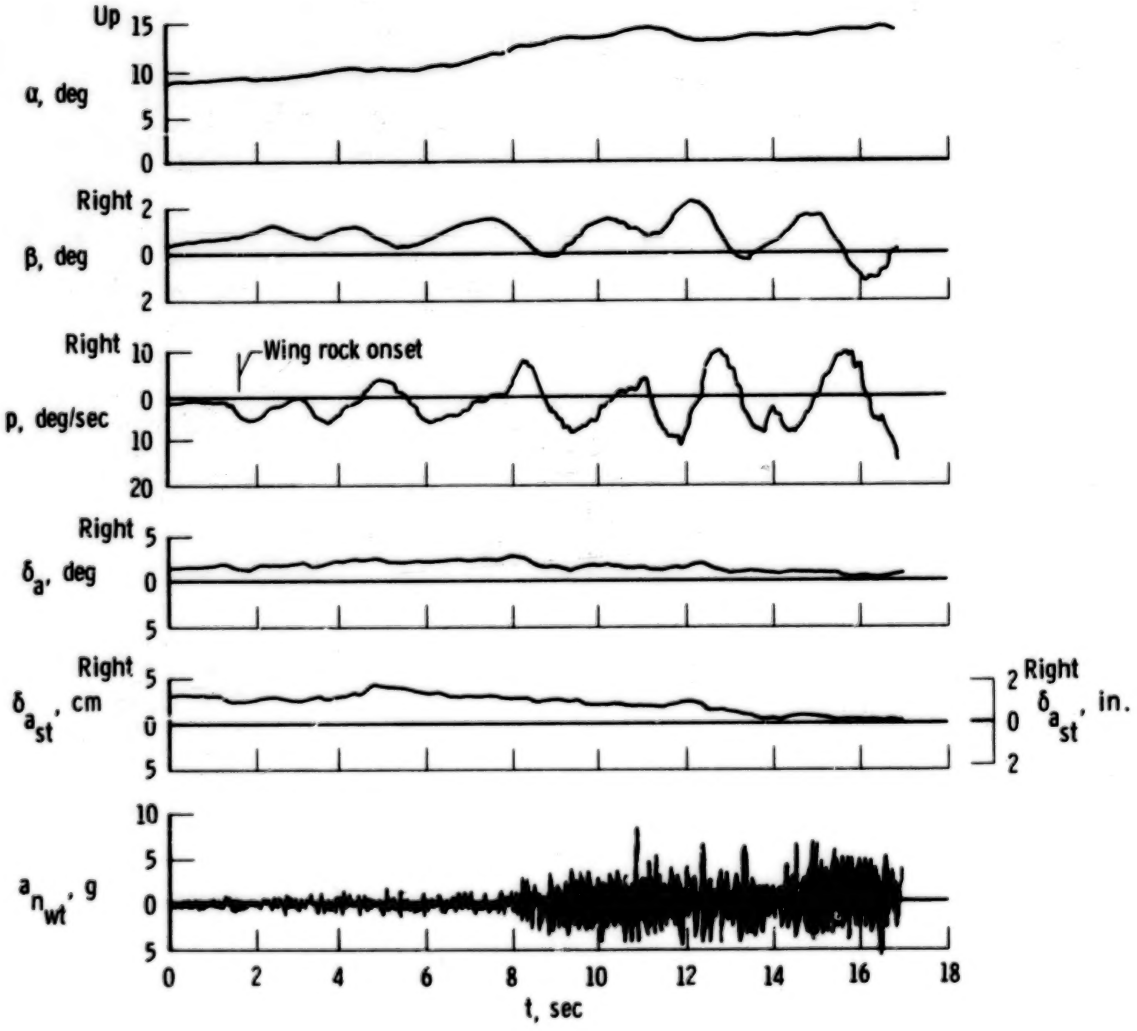
(b) F-111 TACT airplane.

Figure 14. Precision controllability with no handling qualities deficiencies. $\bar{q}$ = 14.4 kN/m^2 (300 lb/ft^2) except as noted.



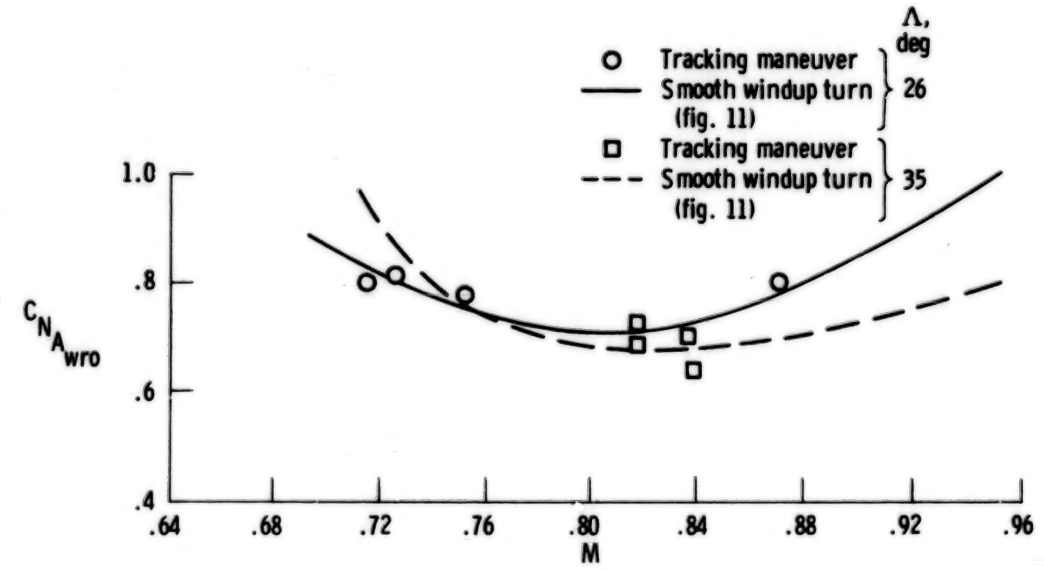
(a) All augmentation on.

Figure 15 Time histories for F-111 TACT airplane illustrating effect of roll augmentation on wing rock. M = 0.88; h_p = 10.05 km (33,000 ft).

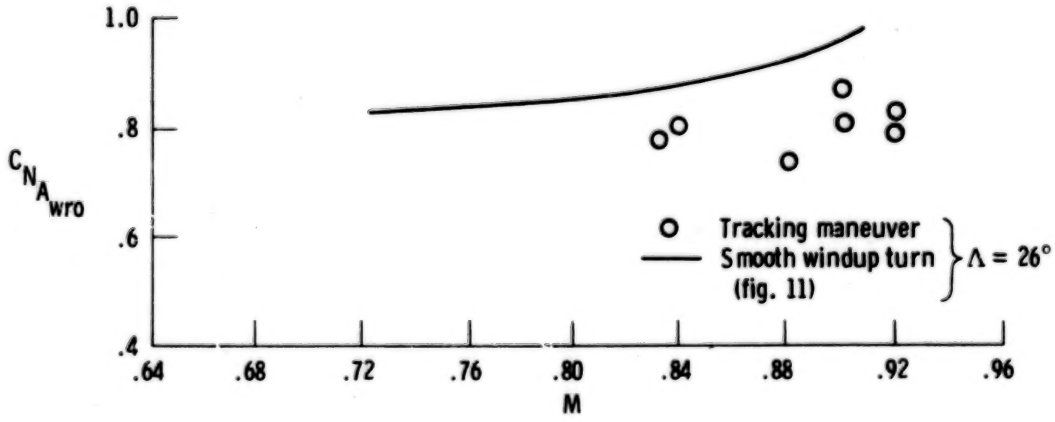


(b) Roll augmentation off.

Figure 15. Concluded.



(a) F-111A airplane.



(b) F-111 TACT airplane.

Figure 16. Comparison of wing rock onset boundaries from smooth windup turns and tailchase tracking maneuvers.

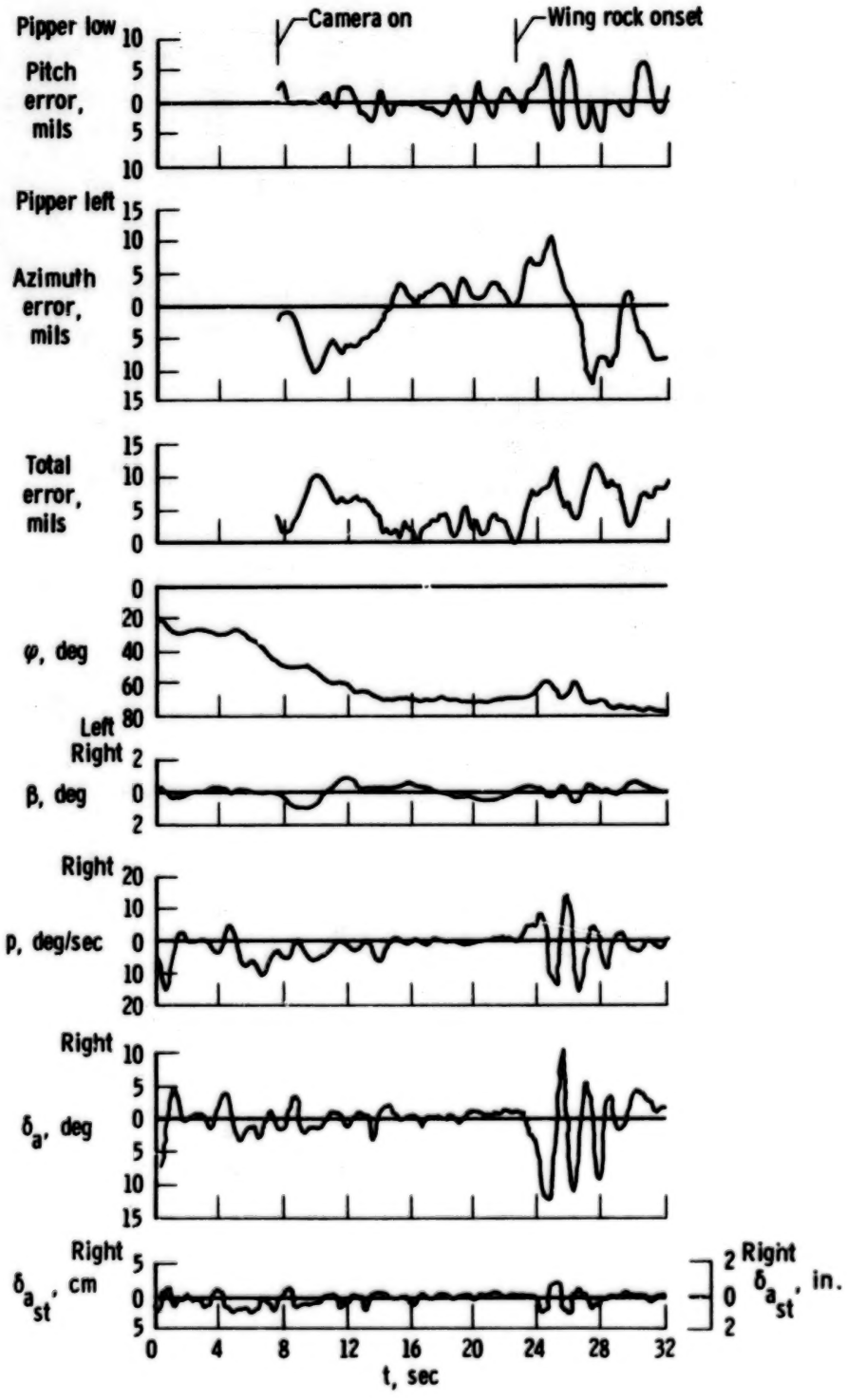
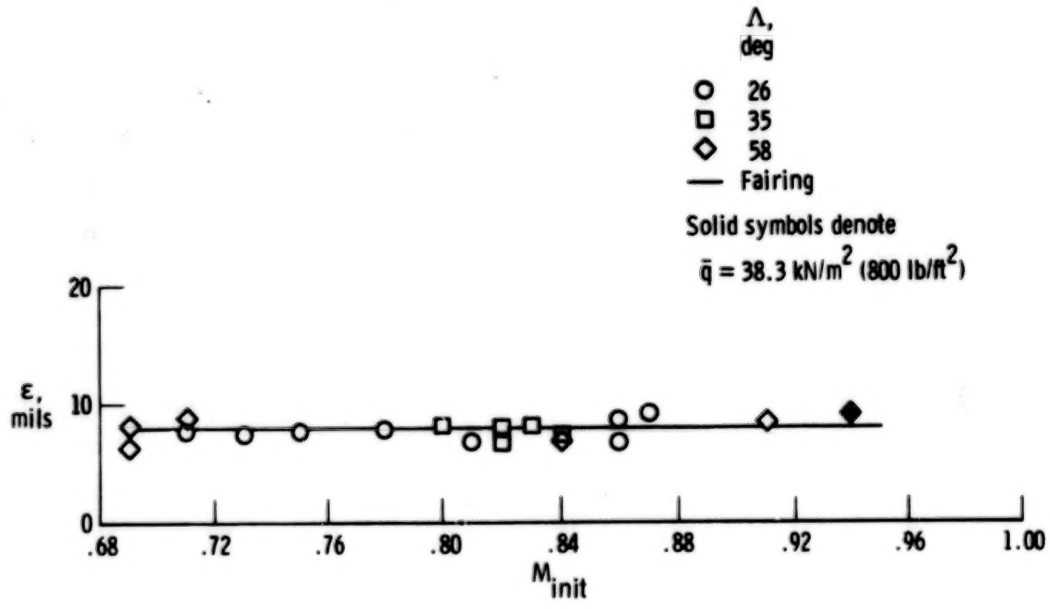
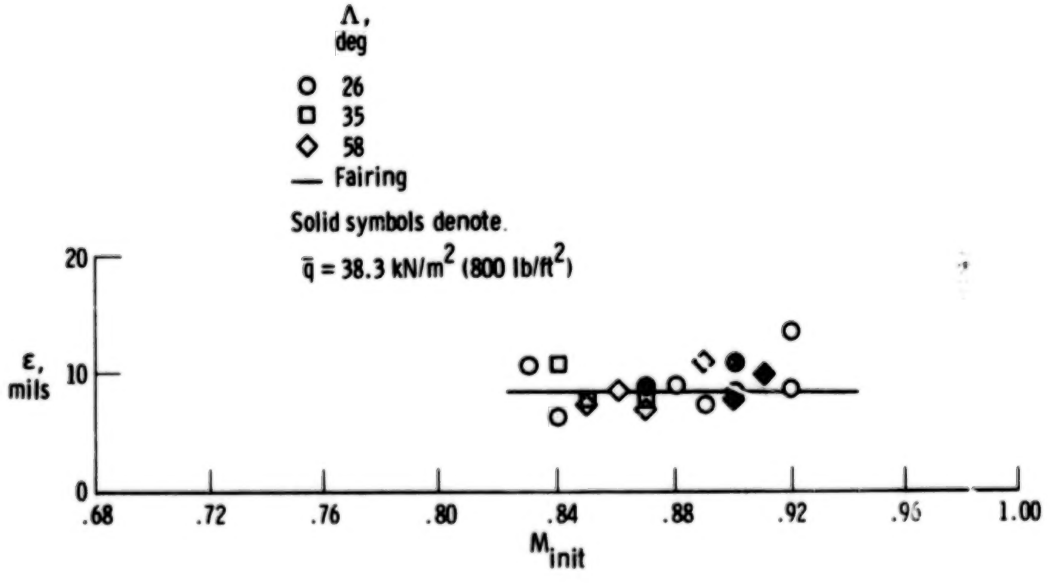


Figure 17. Time history of F-111 TACT tracking windup turn illustrating effects of adverse yaw and wing rock. $M_{init} = 0.88$; $\bar{q} = 14.4$ kN/m^2 (300 lb/ft^2); $\Lambda = 26°$; augmentation on.

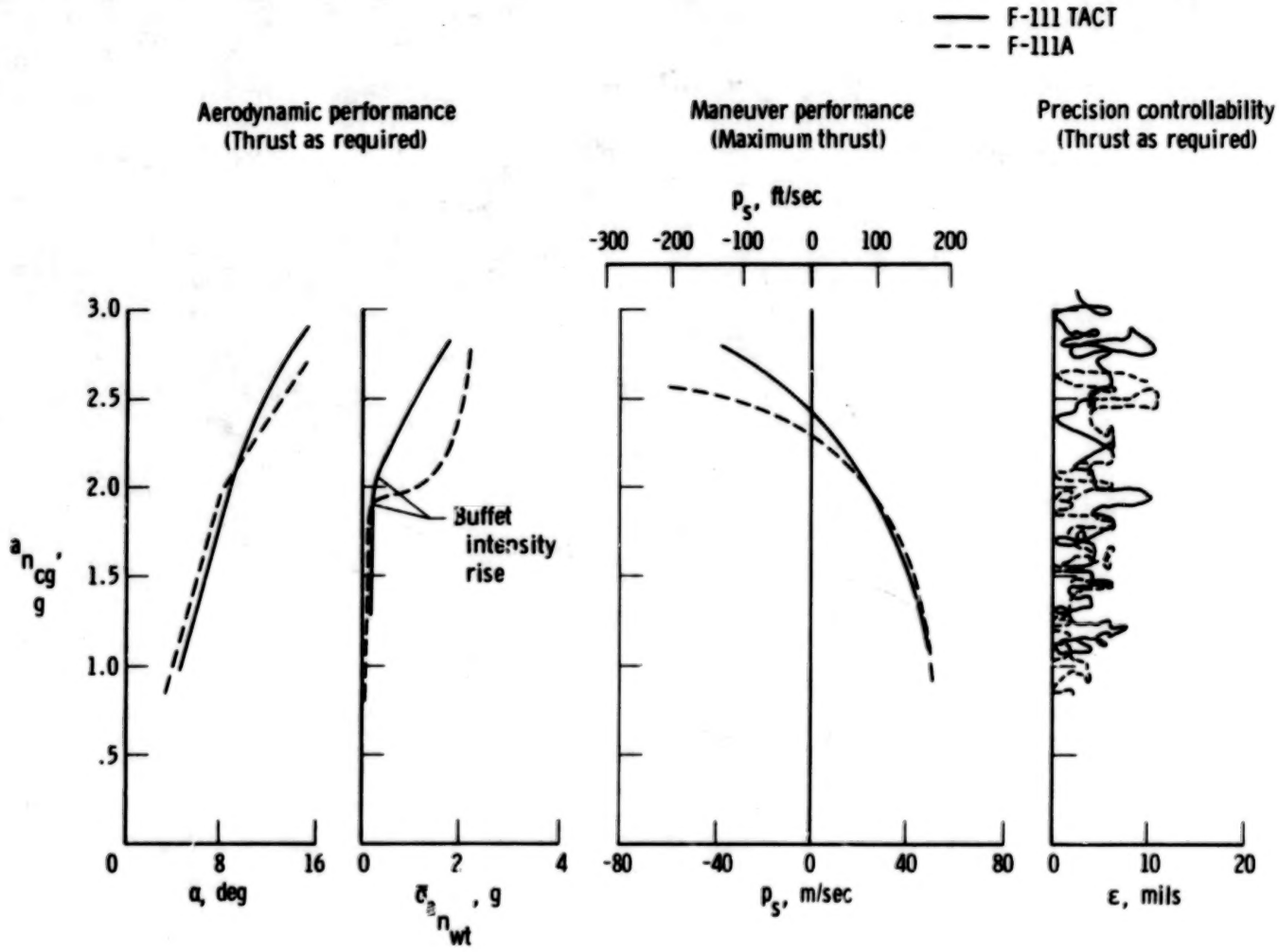


(a) F-111A airplane.



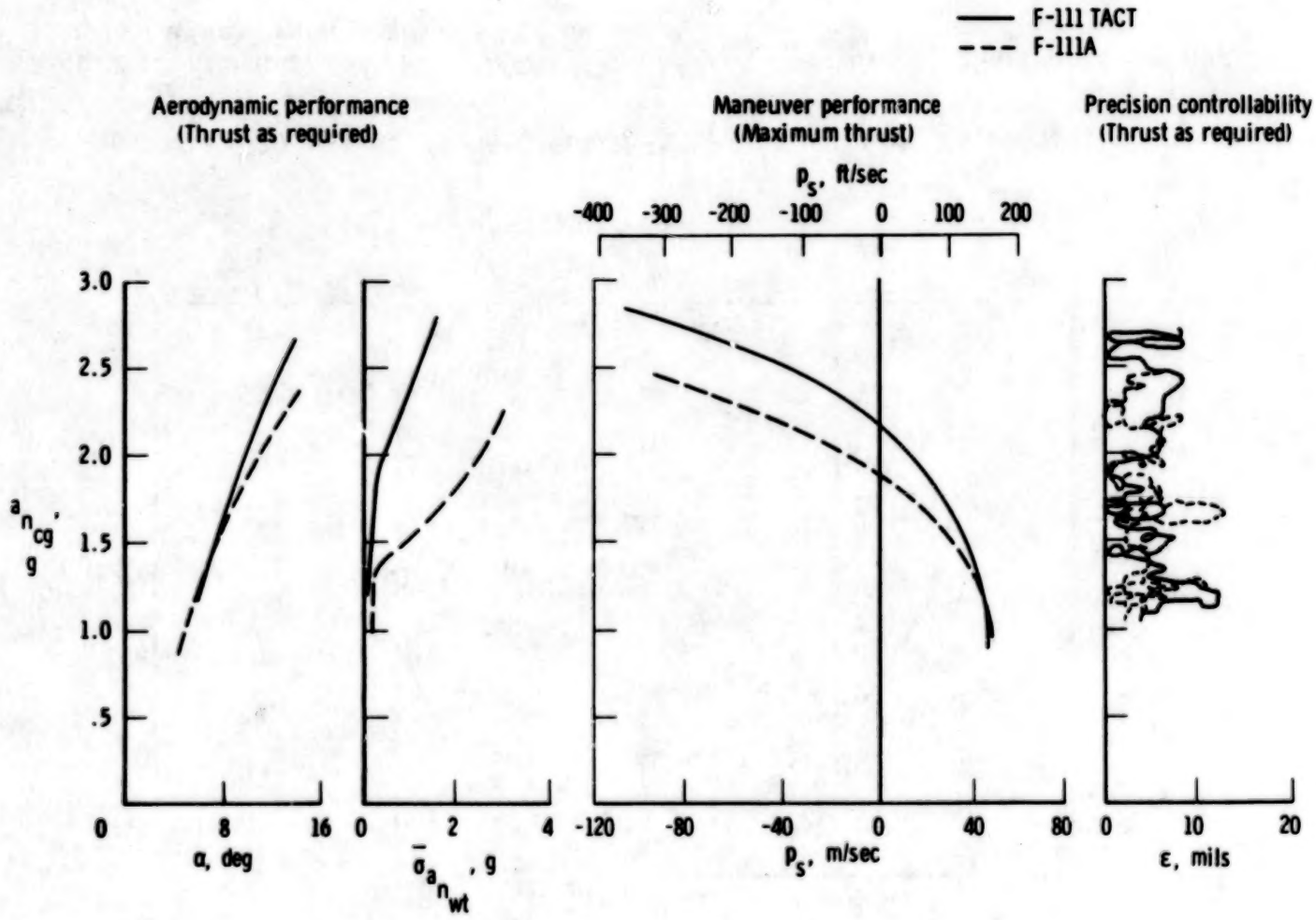
(b) F-111 TACT airplane.

Figure 18. Precision controllability with handling qualities deficiencies. $\bar{q}$ = 14.4 kN/m^2 (300 lb/ft^2) except as noted.



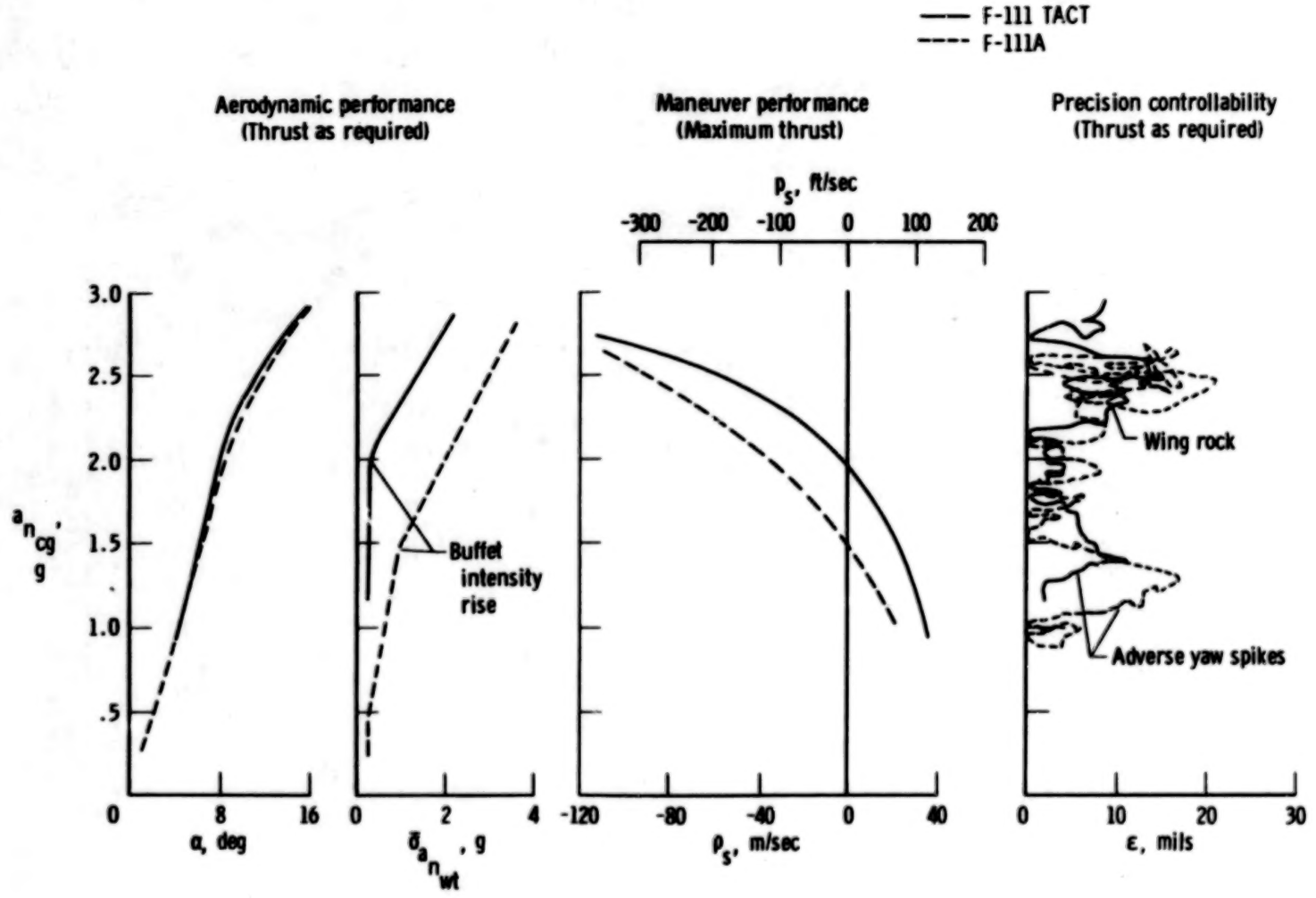
(a) $M = 0.70$, $\bar{q} = 14.4$ kN/m^2 (300 lb/ft^2), $W = 289.1$ kN (65,000 lb), $\Lambda = 26°$.

Figure 19. Comparison of F-111 TACT and F-111A aircraft over Mach number range for identical wing-sweep positions.



(b) $M = 0.80$, $\bar{q} = 14.4\ kN/m^2$ (300 lb/ft^2), $W = 289.1\ kN$ (65,000 lb), $\Lambda = 35°$.

Figure 19. Continued.



(c) $M = 0.88$, $\bar{q} = 14.4\ kN/m^2$ $(300\ lb/ft^2)$, $W = 289.1\ kN$ $(65,000\ lb)$, $\Lambda = 26°$.

Figure 19. Concluded.

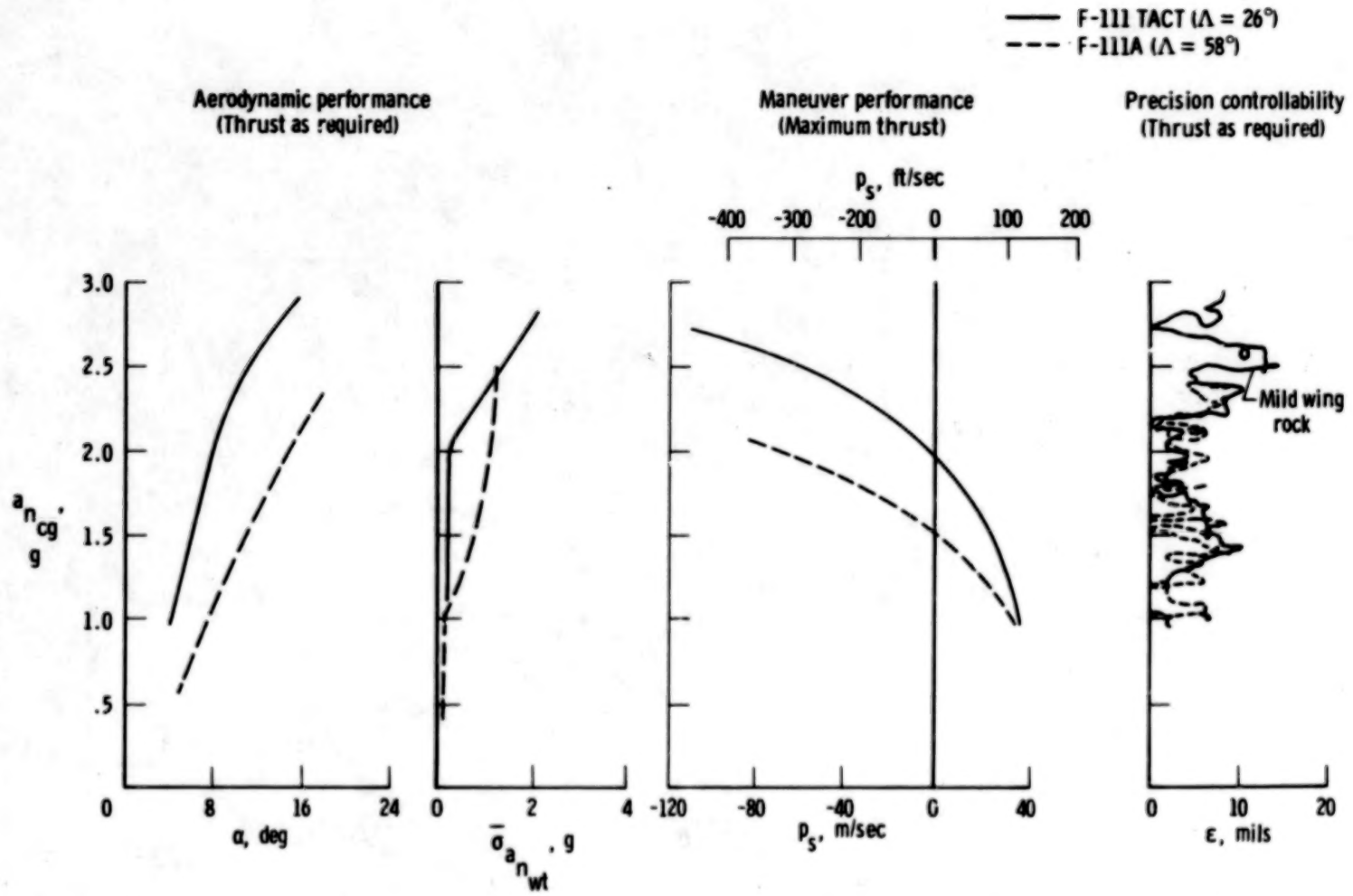


Figure 20. Comparison of F-111 TACT and F-111A aircraft for optimum wing-sweep positions. $M = 0.88$; $\bar{q} = 14.4\ kN/m^2$ (300 lb/ft^2); $W = 289.1\ kN$ (65,000 lb).

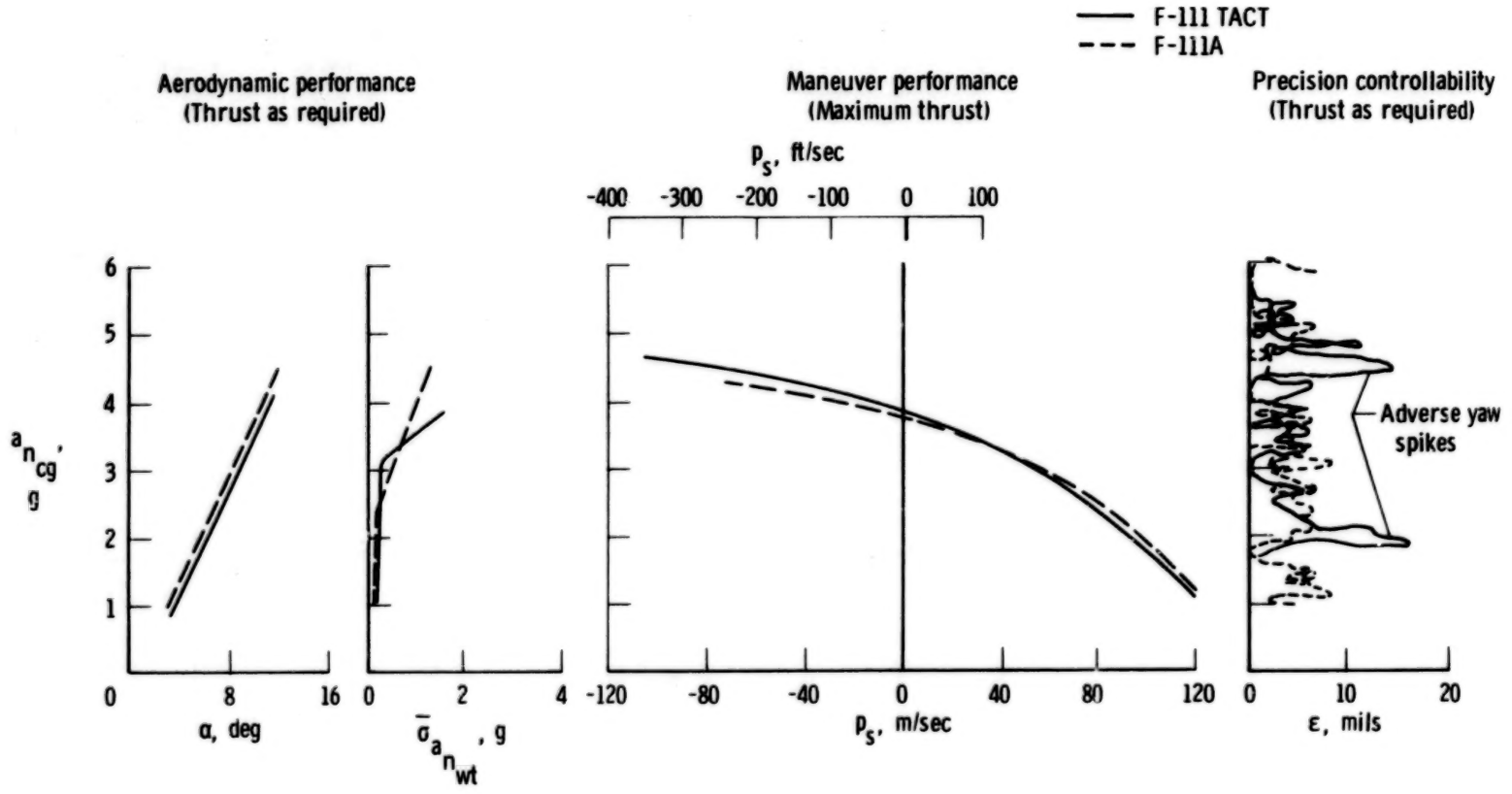


Figure 21. Comparison of F-111 TACT and F-111A aircraft at F-111 TACT design point for identical wing-sweep positions. M = 0.90; $\bar{q}$ = 38.3 kN/m^2 (800 lb/ft^2); W = 289.1 kN (65,000 lb); Λ = 58°.

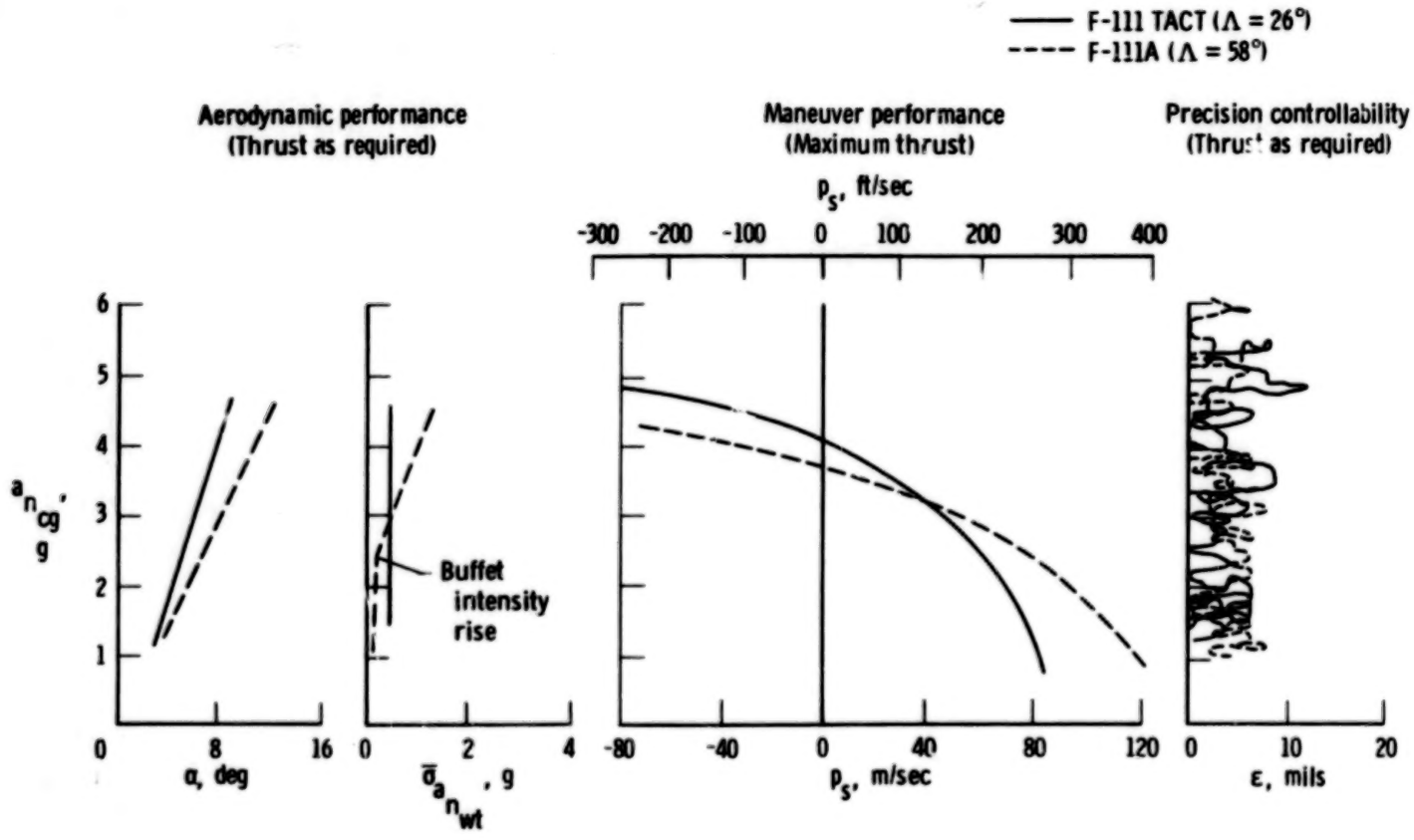
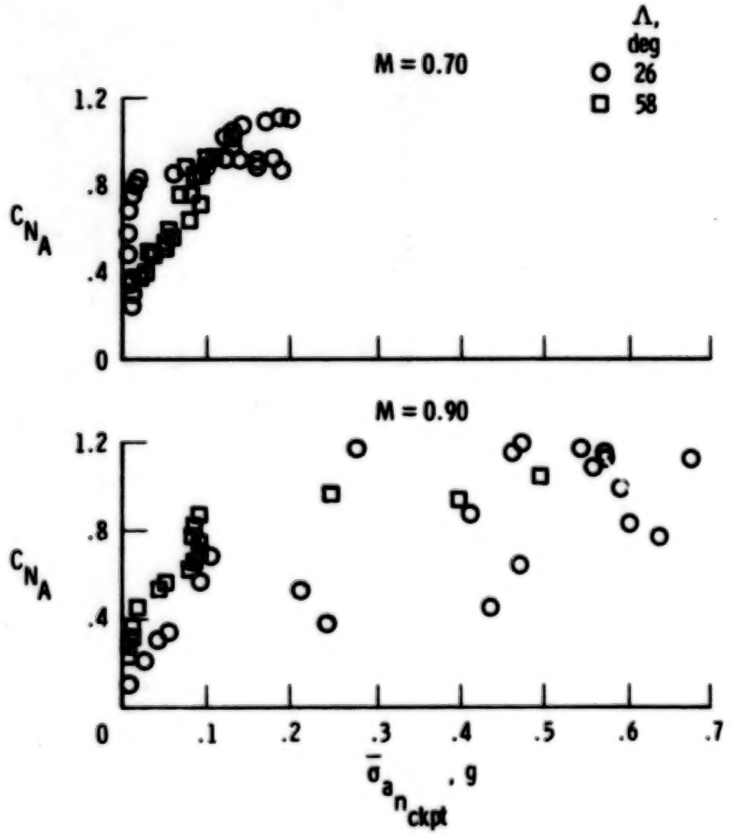
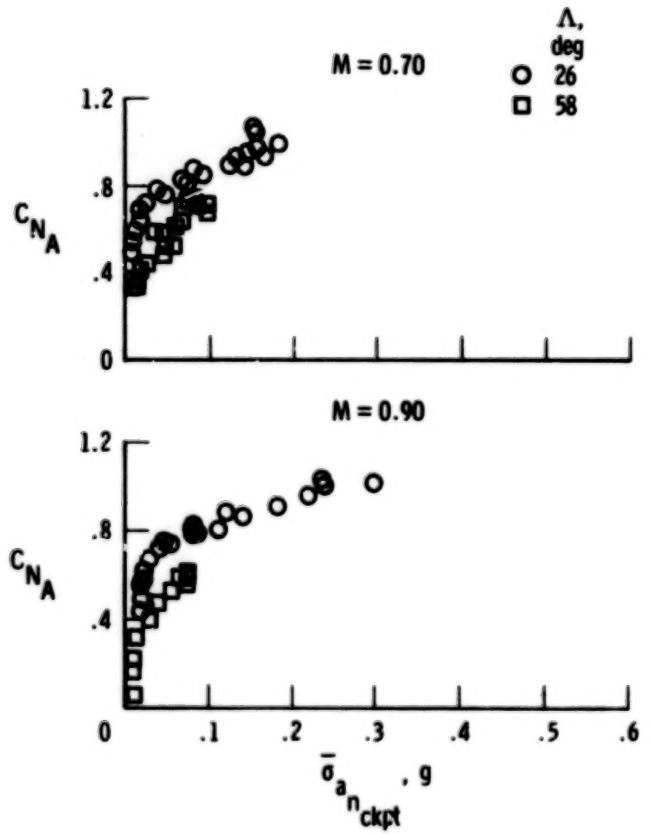


Figure 22. Comparison of F-111 TACT and F-111A aircraft at F-111 TACT design point for optimum wing-sweep positions. M = 0.90; $\bar{q}$ = 38.3 kN/m^2 (800 lb/ft^2); W = 289.1 kN (65,000 lb).



(a) F-111A airplane.



(b) F-111 TACT airplane.

Figure 23. Comparison of F-111A and F-111 TACT pilot station buffet characteristics.

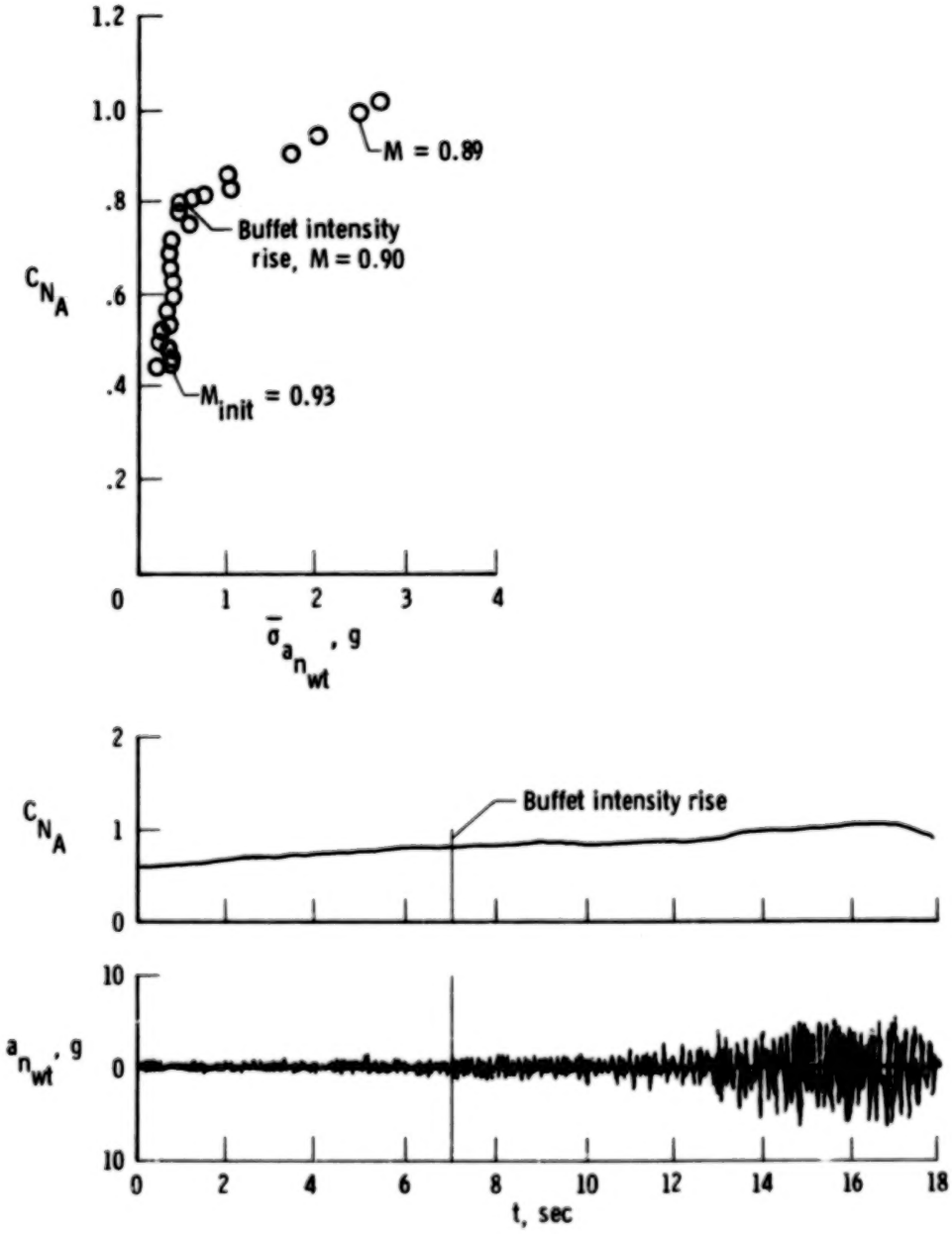
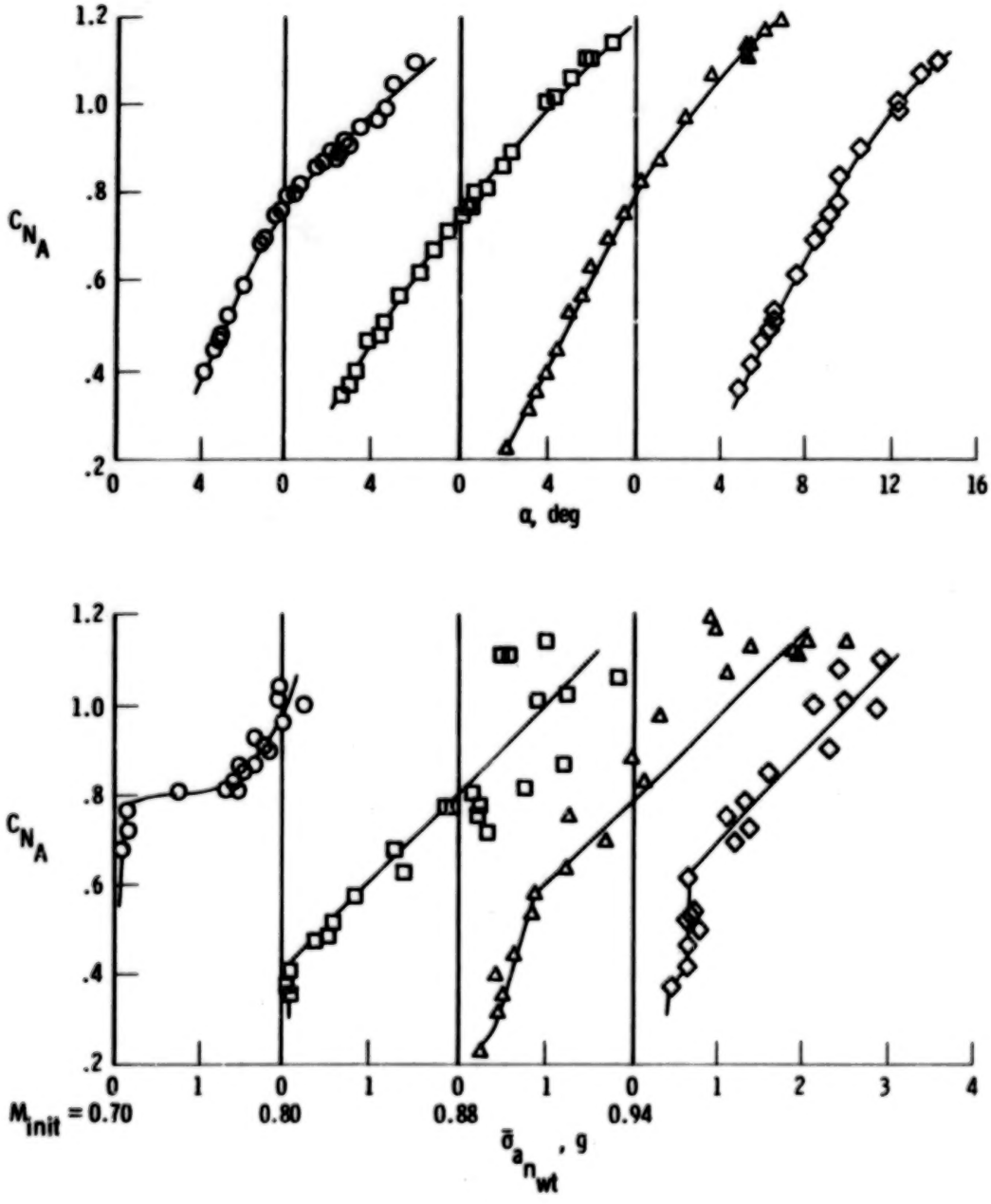
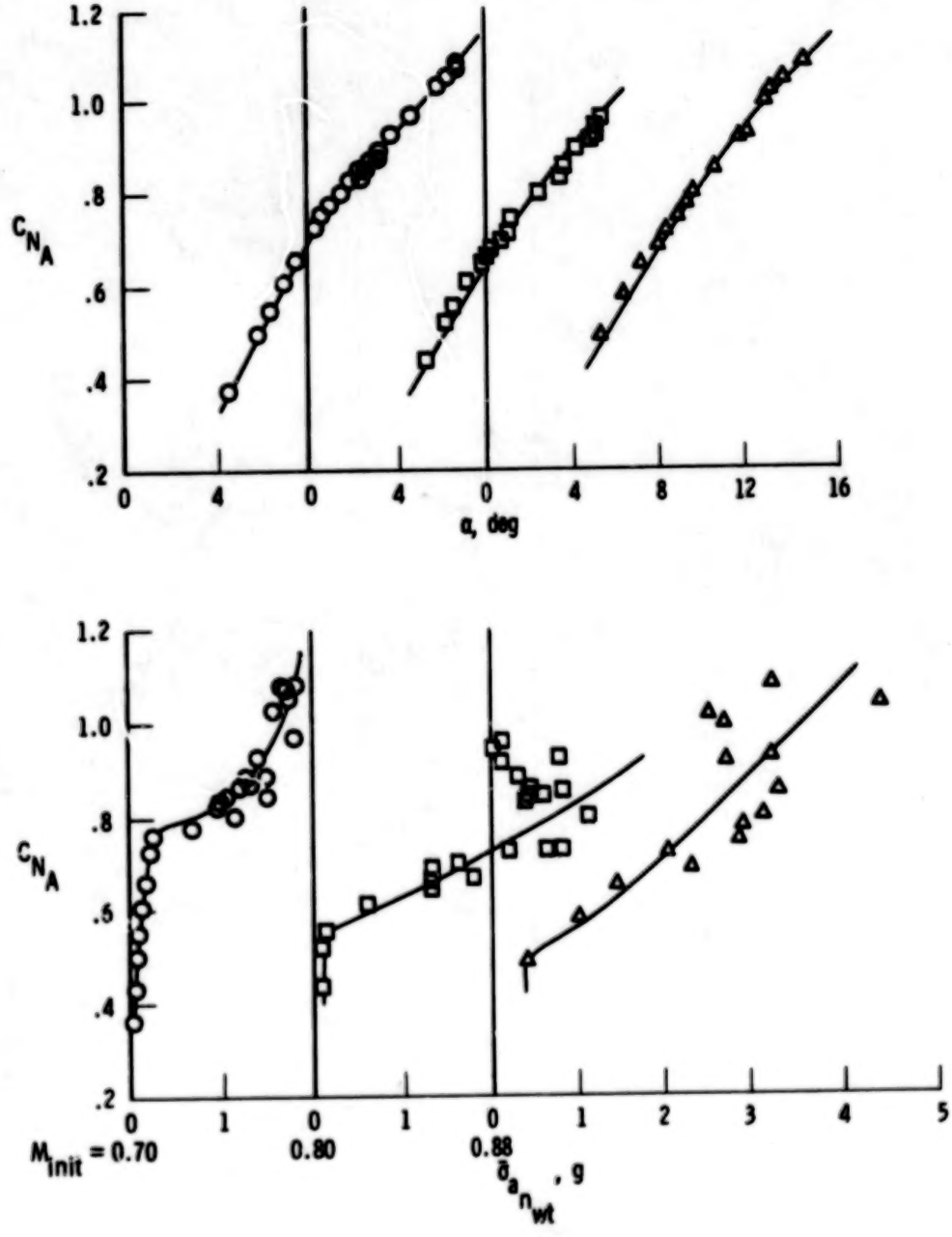


Figure 24. Buffet intensity rise determination.



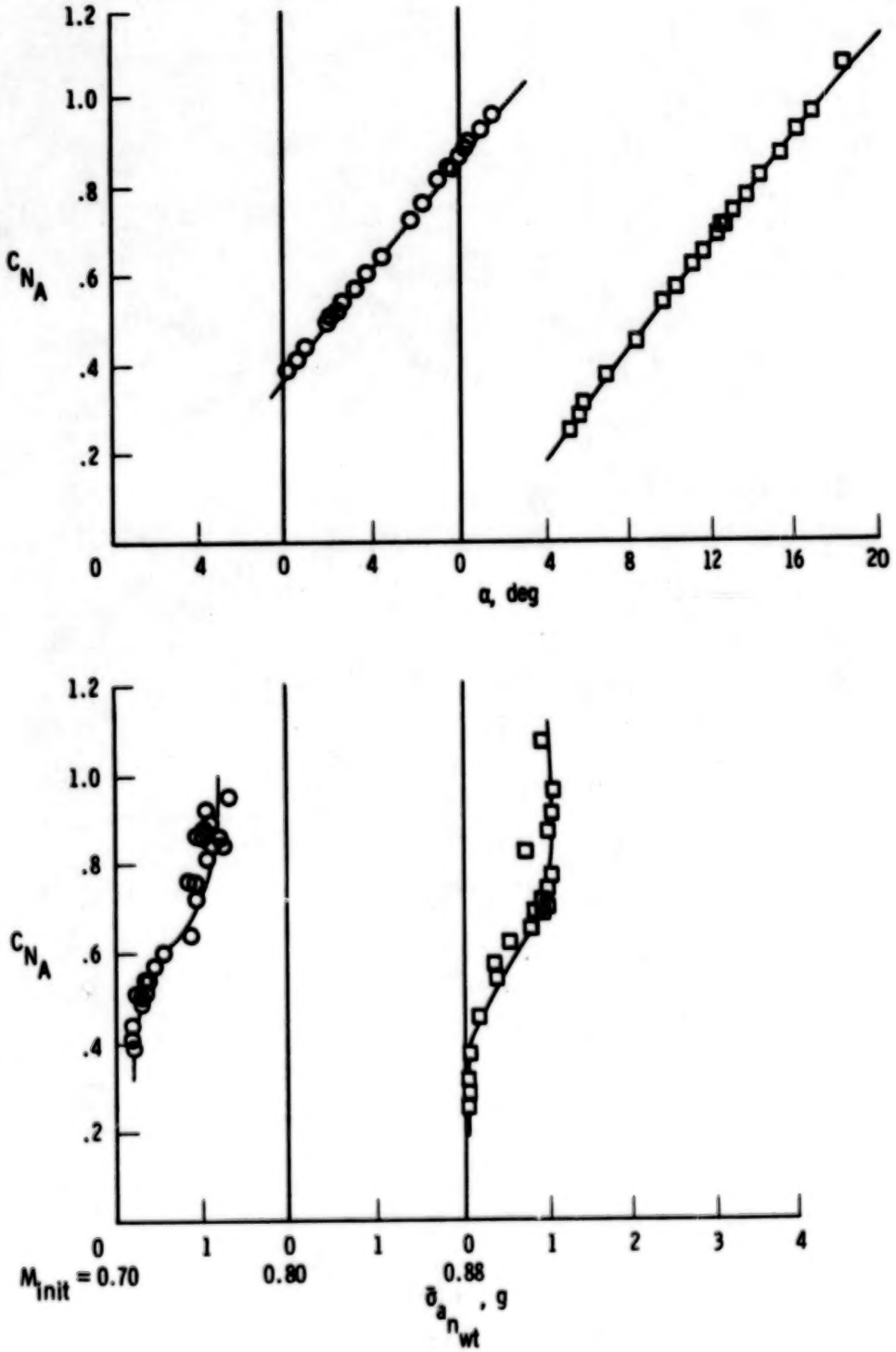
(a) $\Lambda = 26°$.

Figure 25. F-111A aerodynamic summary for $\bar{q} = 14.4$ *kN/m*^{2} *(300 lb/ft*^{2}*).*



(b) $\Lambda = 35°$.

Figure 25. Continued.



(c) $\Lambda = 58°$.

Figure 25. Concluded.

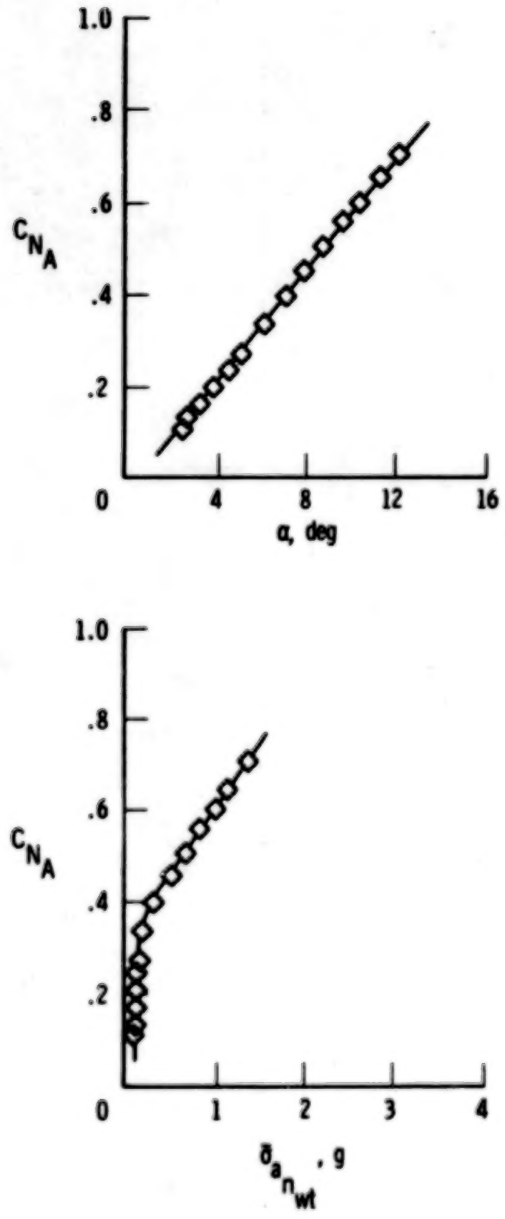
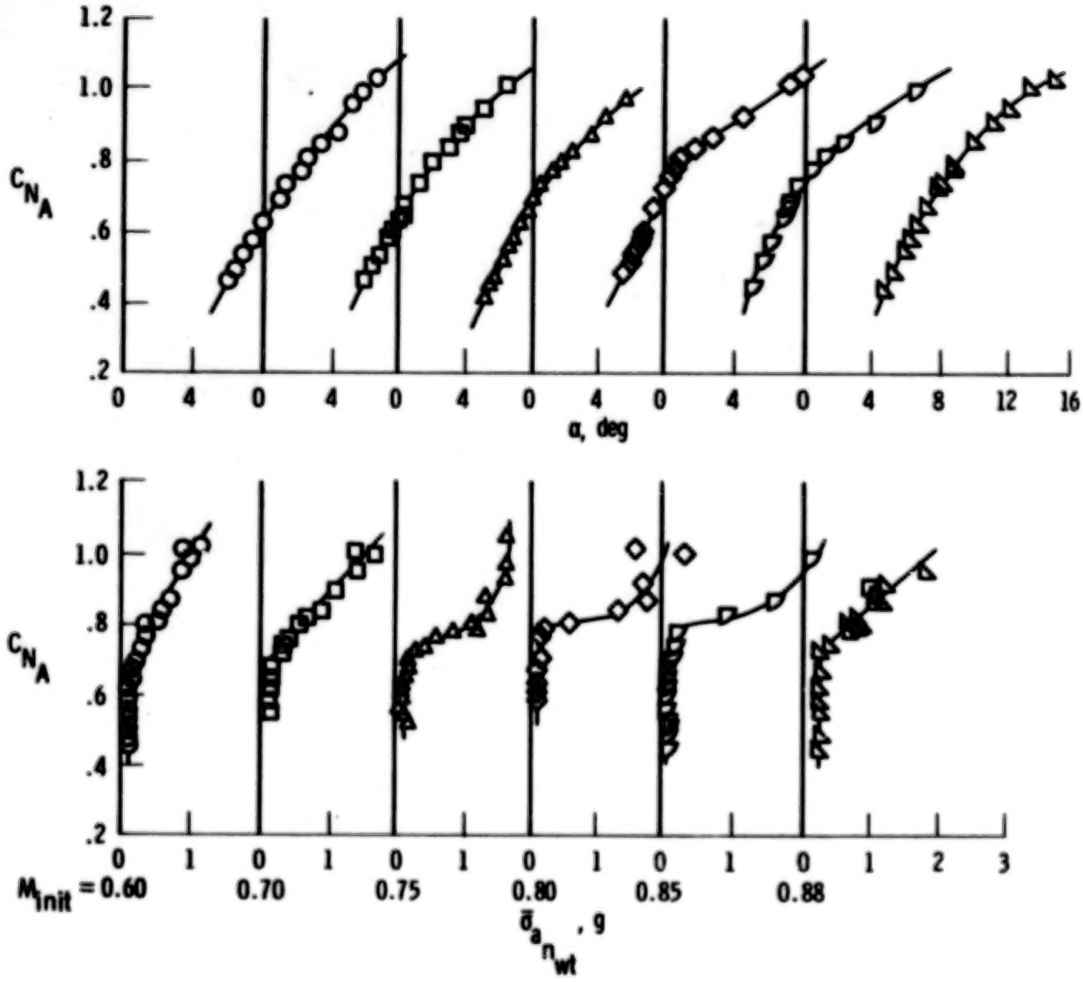
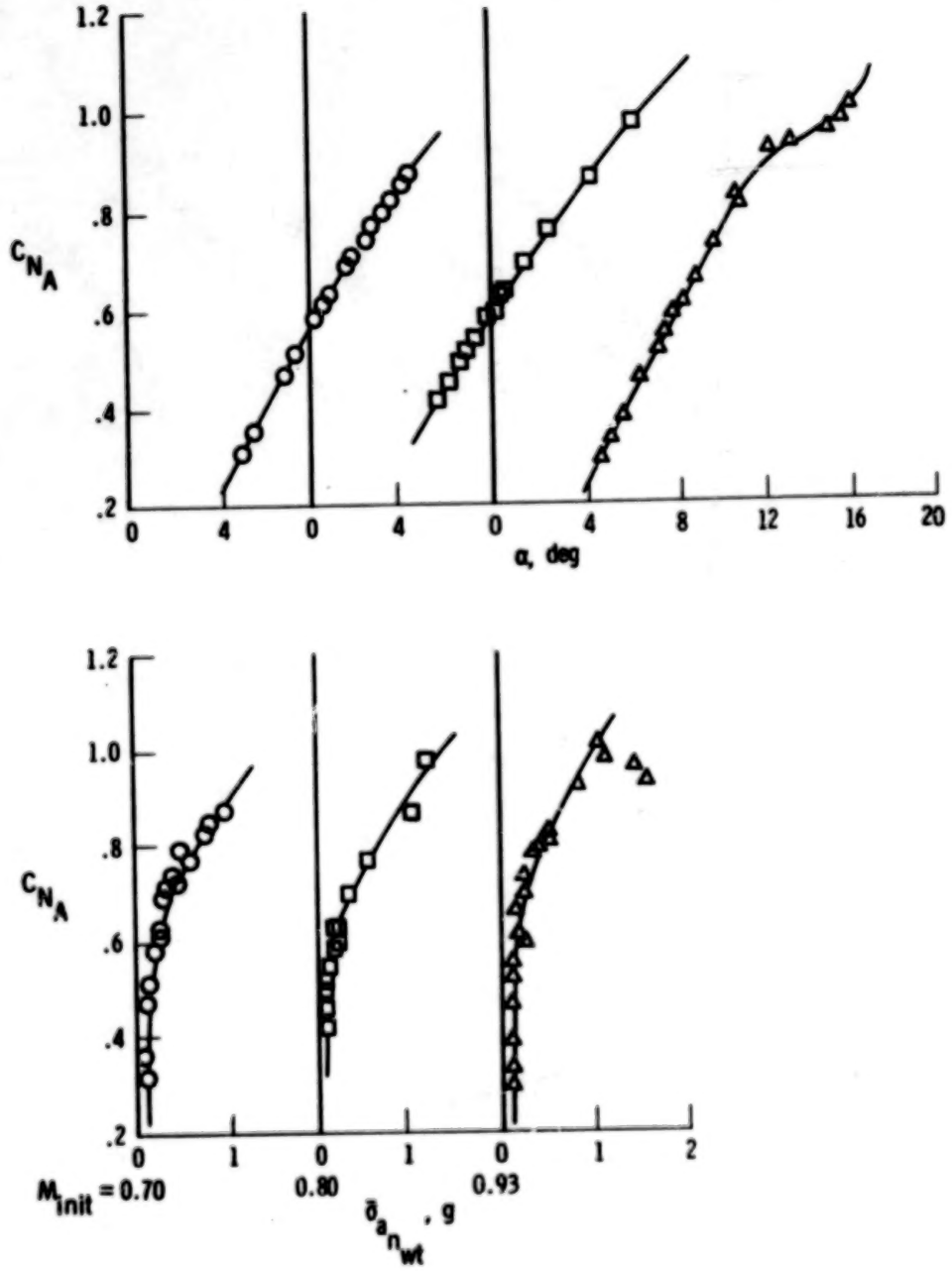


Figure 26. F-111A aerodynamic summary for $\bar{q}$ = 38.3 kN/m^2 (800 lb/ft^2). M = 0.90; Λ = 58°.



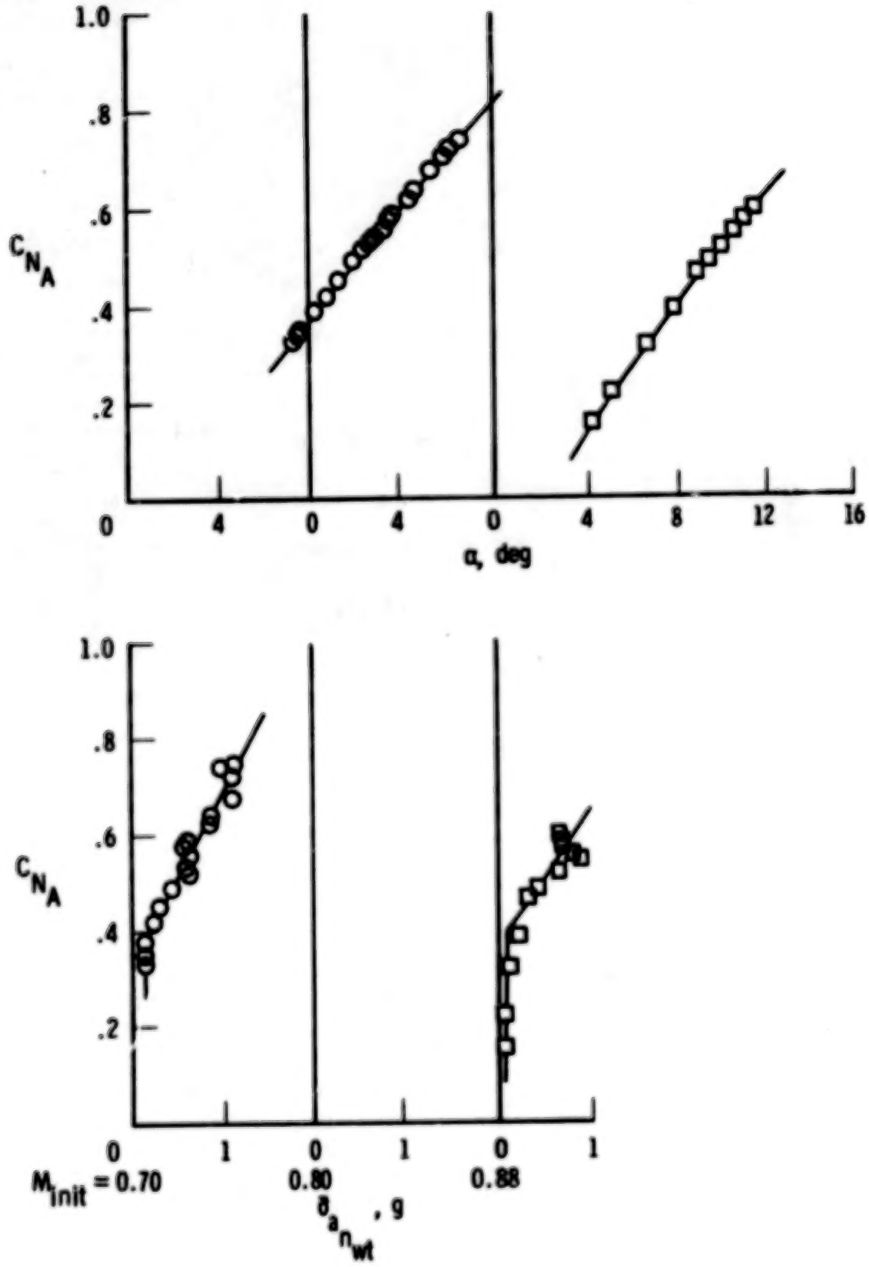
(a) $\Lambda = 26°$.

Figure 27. F-111 TACT aerodynamic summary for $\bar{q} = 14.4$ kN/m^2 *(300 lb/ft^2).*



(b) $\Lambda = 35°$.

Figure 27. Continued.



(c) $\Lambda = 58°$.

Figure 27. Concluded.

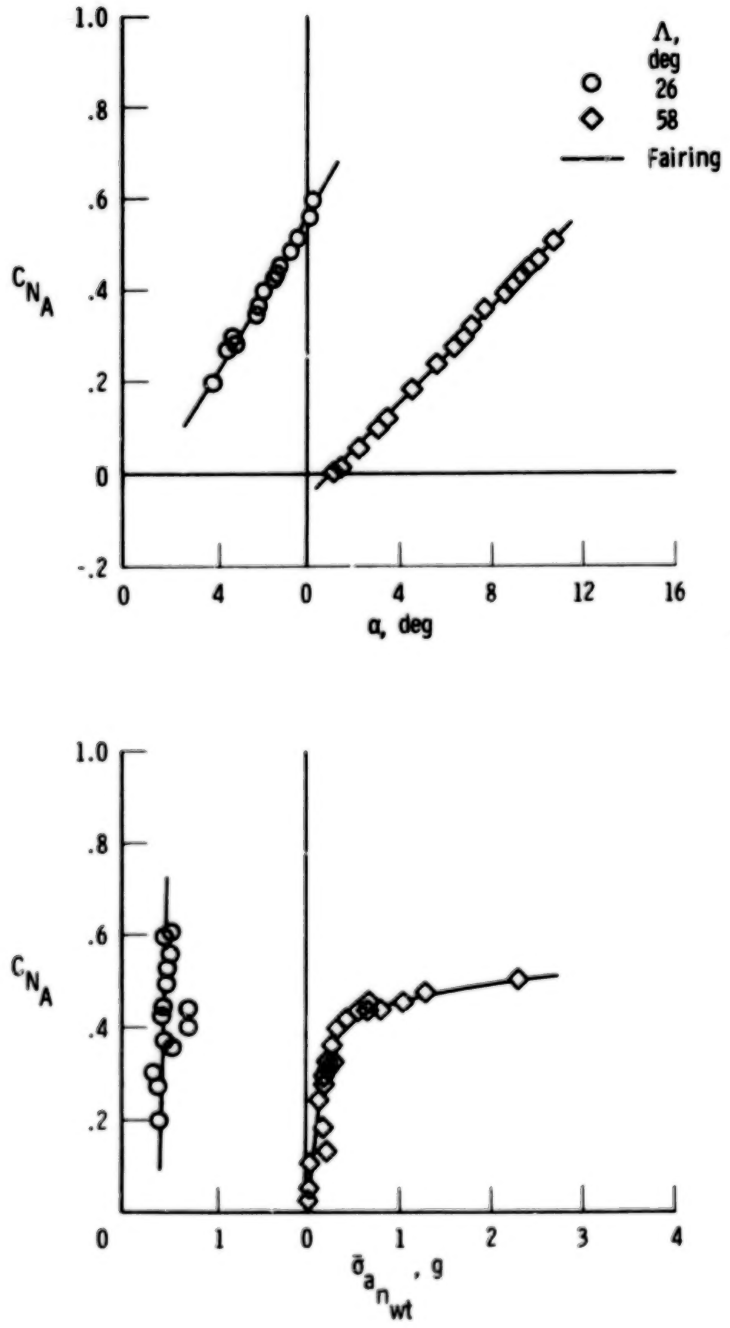
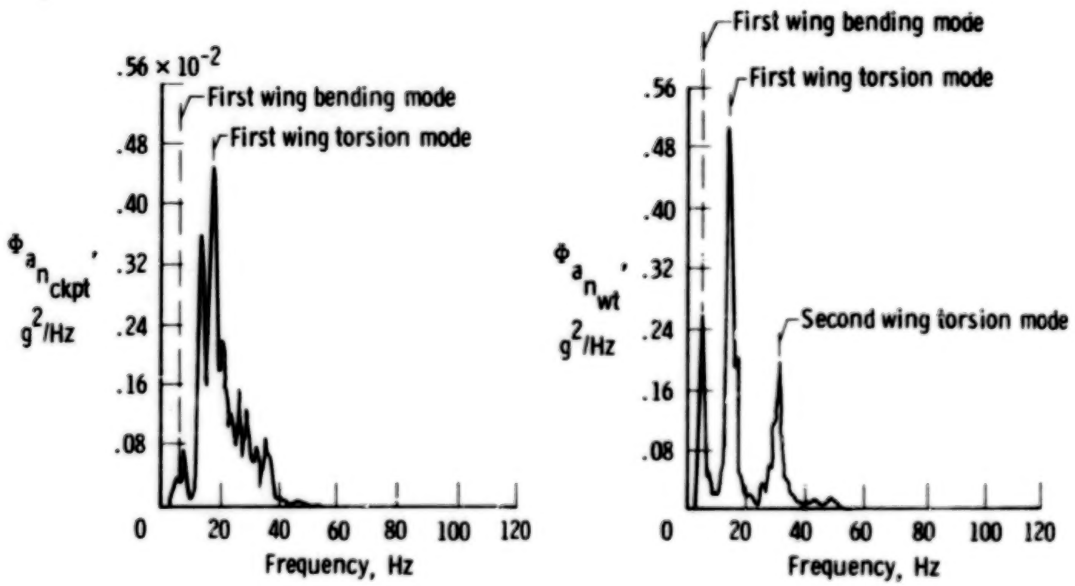
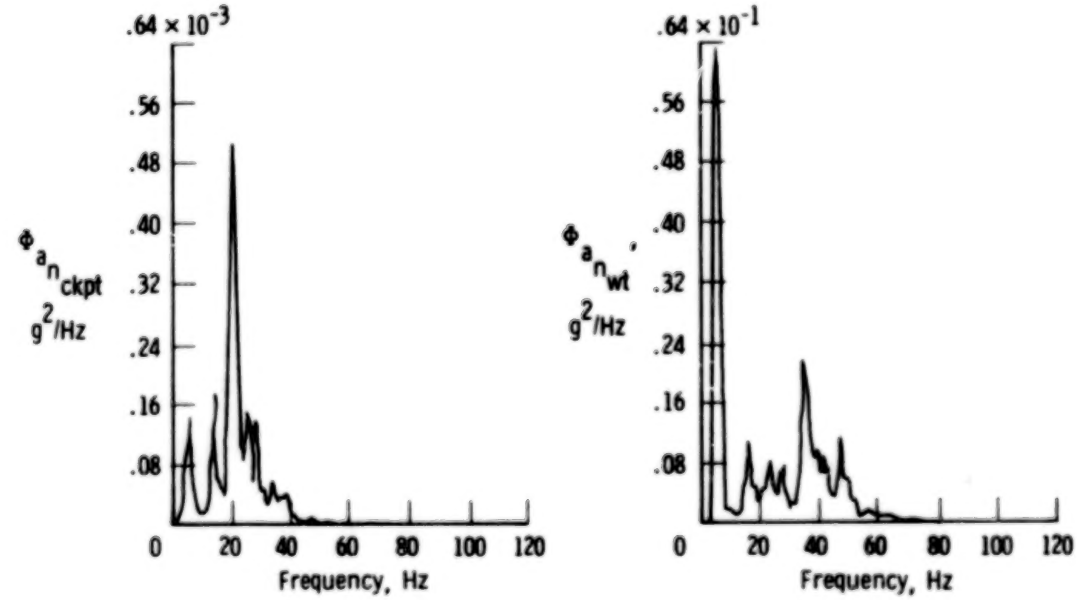


Figure 28. F-111 TACT aerodynamic summary for $\bar{q}$ = 38.3 kN/m^2 (800 lb/ft^2). M = 0.90.

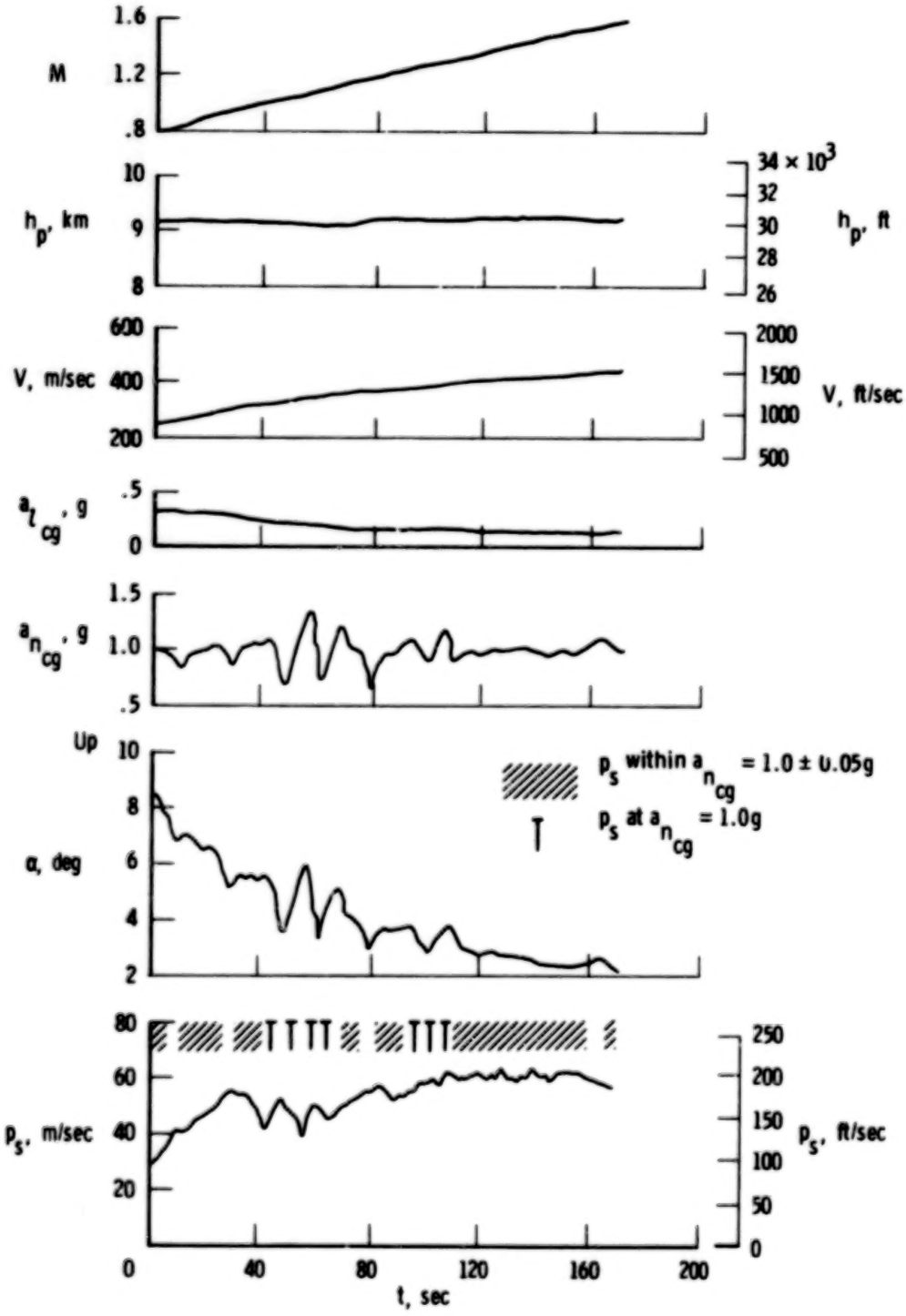


(a) $M_{init} = 0.82$, $\Lambda = 26°$, $\alpha_{init} = 10°$.



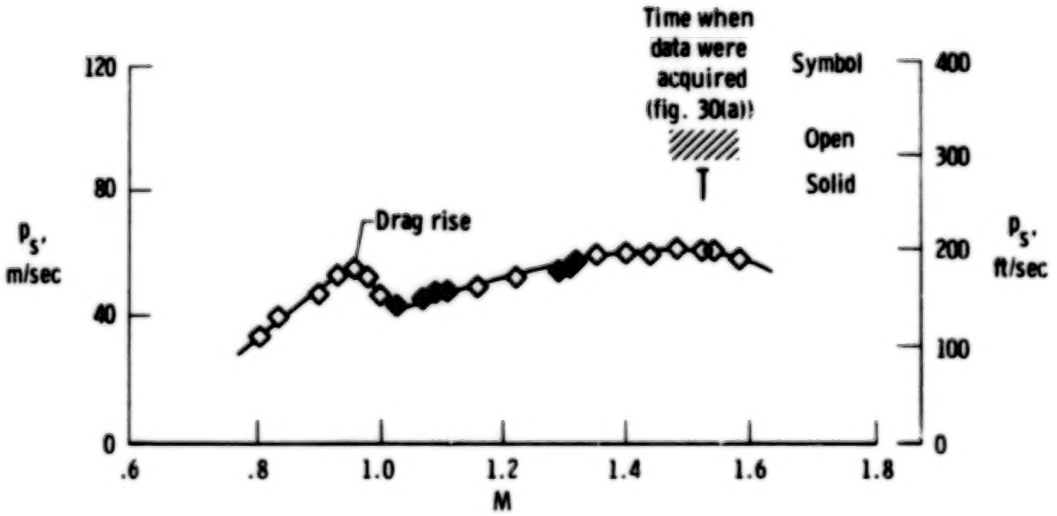
(b) $M_{init} = 0.88$, $\Lambda = 58°$, $\alpha_{init} = 11°$.

Figure 29. PSD analysis of F-111 TACT buffet data.



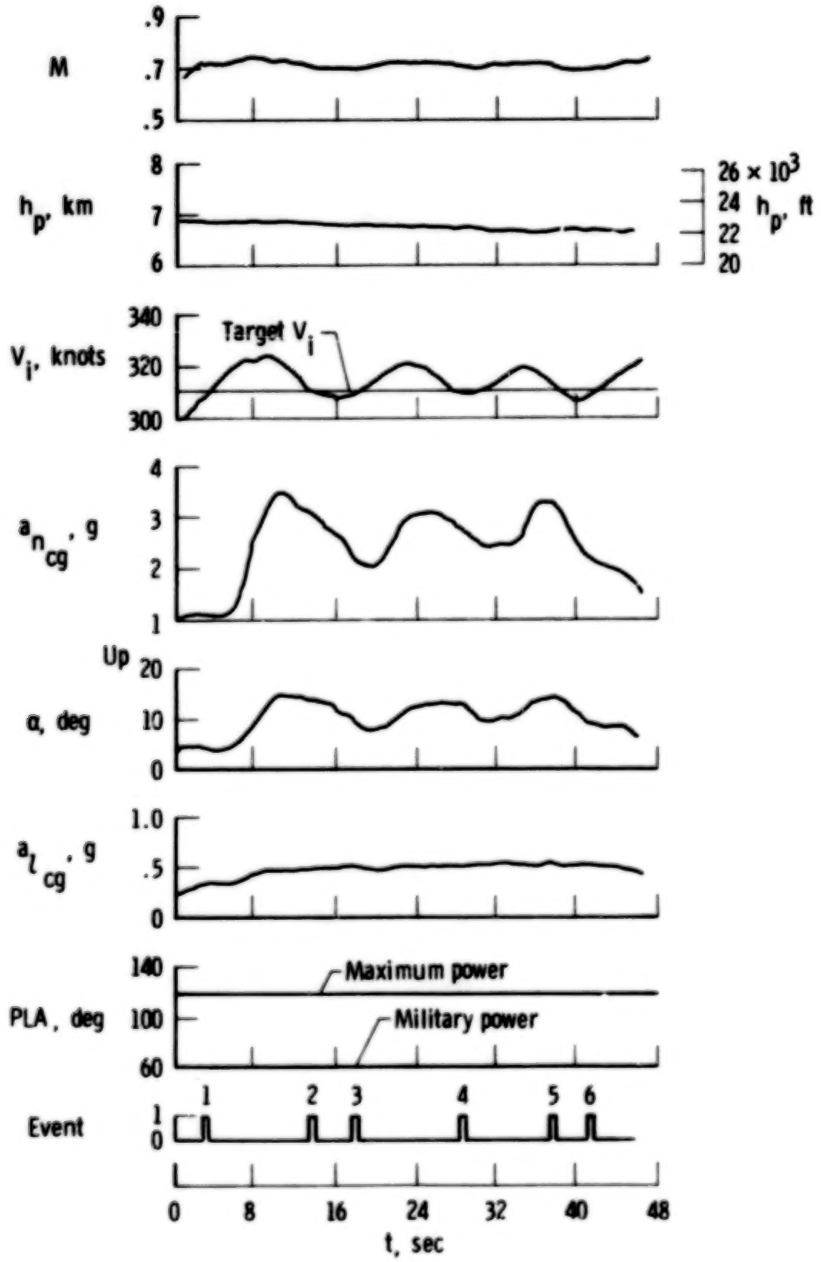
(a) Time history.

Figure 30. Specific excess power variation for F-111A airplane during maximum power level acceleration. h_p = 9.14 km (30,000 ft); Λ = 58°.



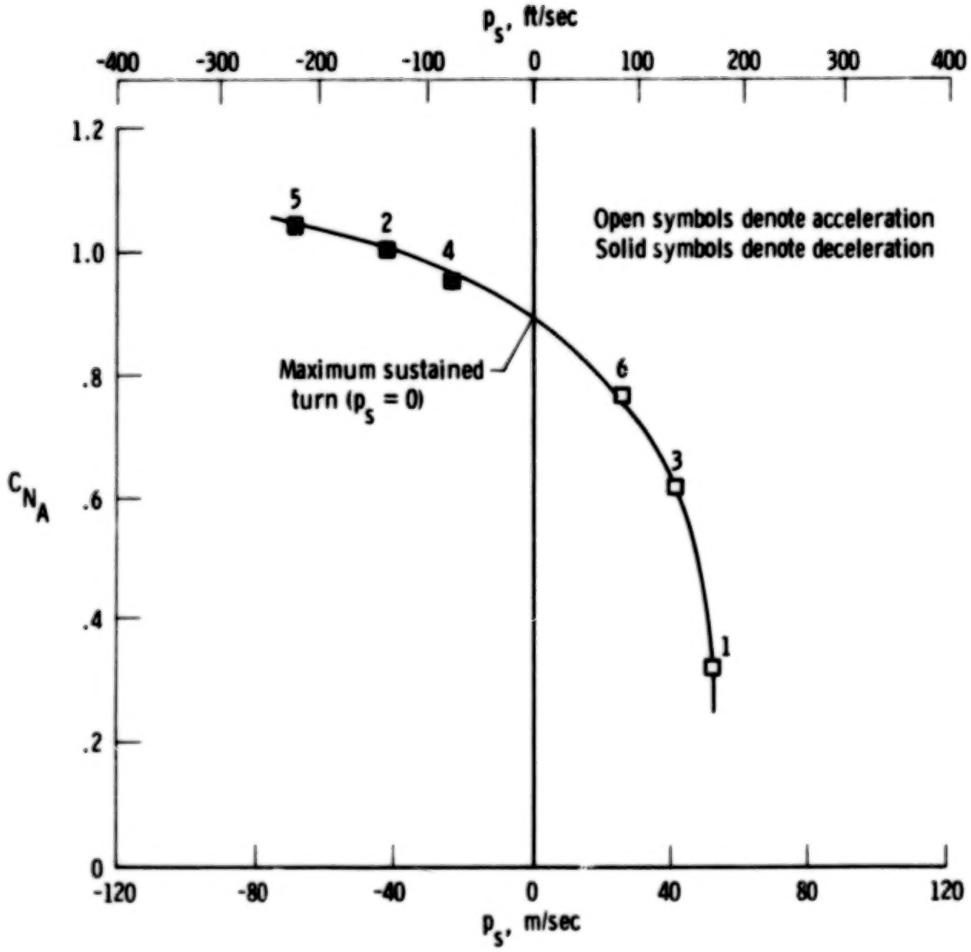
(b) lg specific excess power variation.

Figure 30. Concluded.



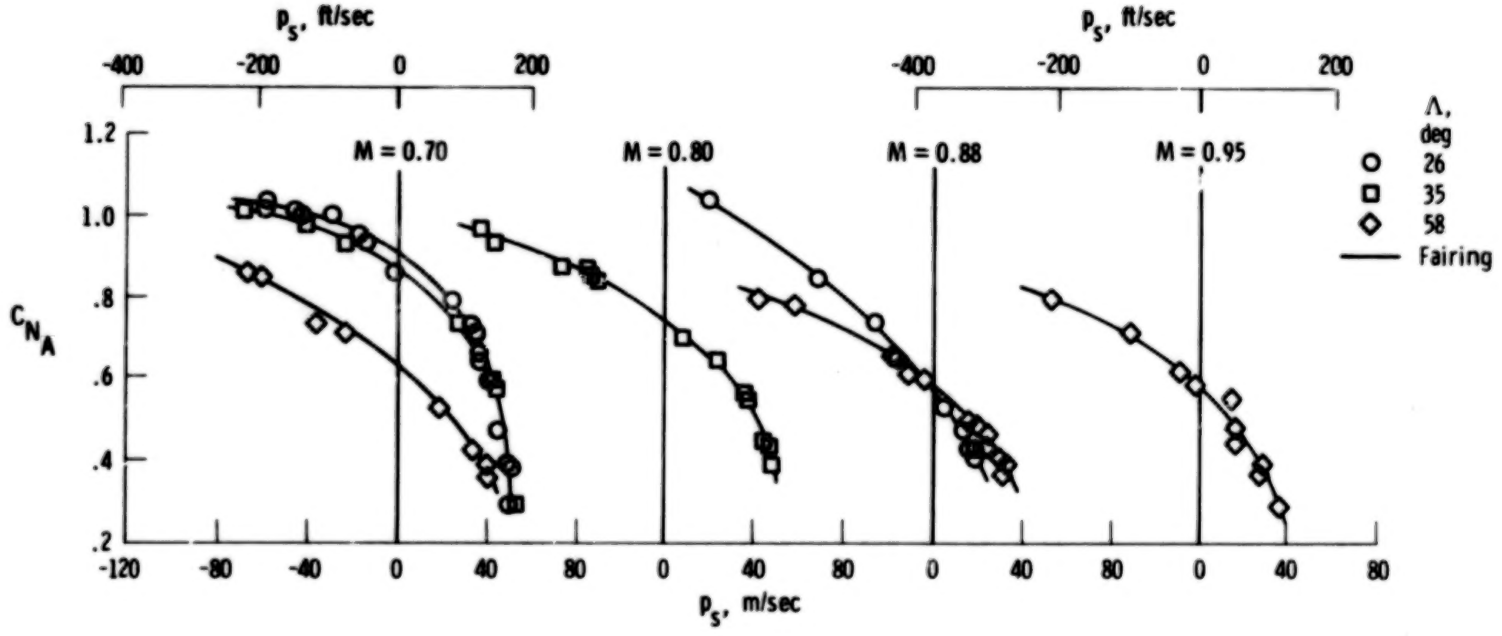
(a) Time history.

Figure 31. Specific excess power variation at constant Mach number for F-111A airplane at M = 0.70. h_p = 6.86 km (22,500 ft); Λ = 35°.



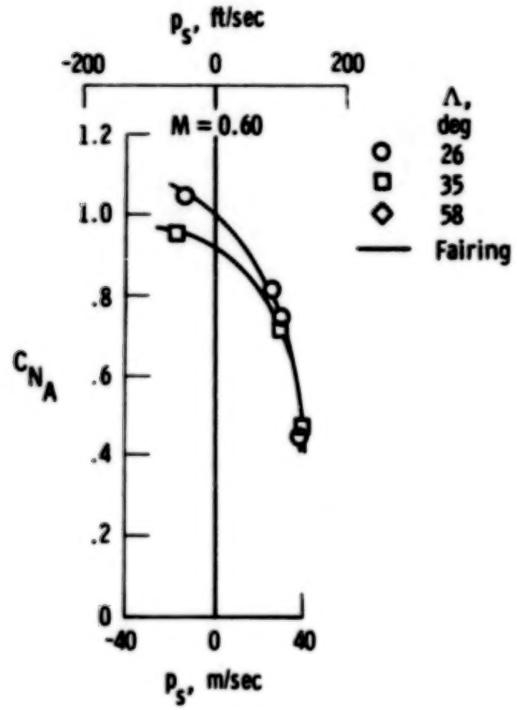
(b) Specific excess power variation.

Figure 31. Concluded.

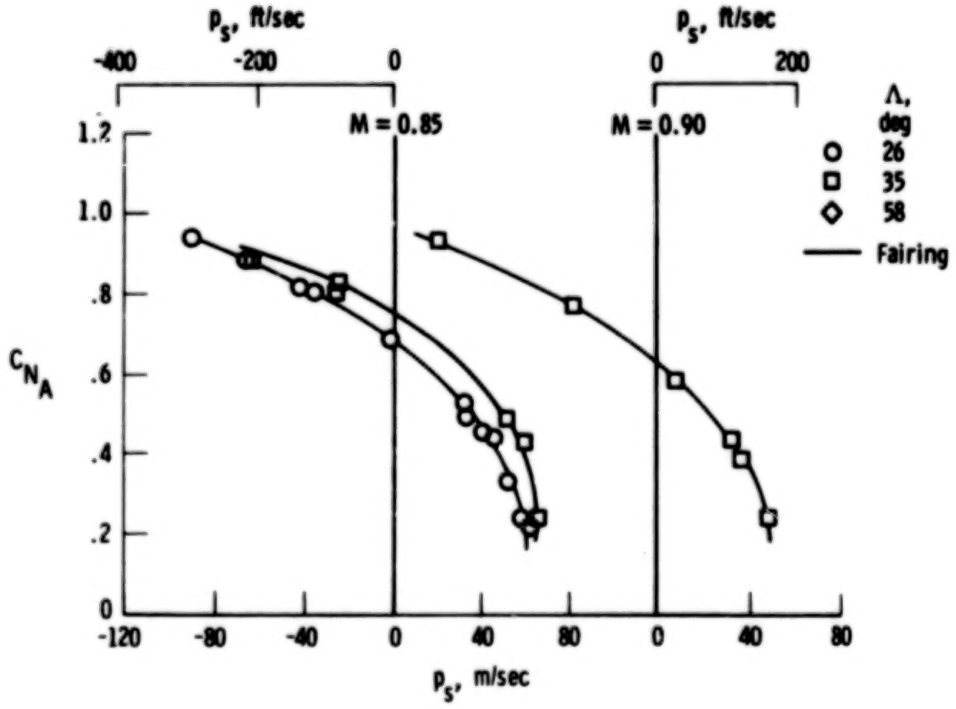


(a) $\bar{q} = 14.4\ kN/m^2$ *(300* lb/ft^2*).*

Figure 32. Specific excess power data for F-111A airplane.

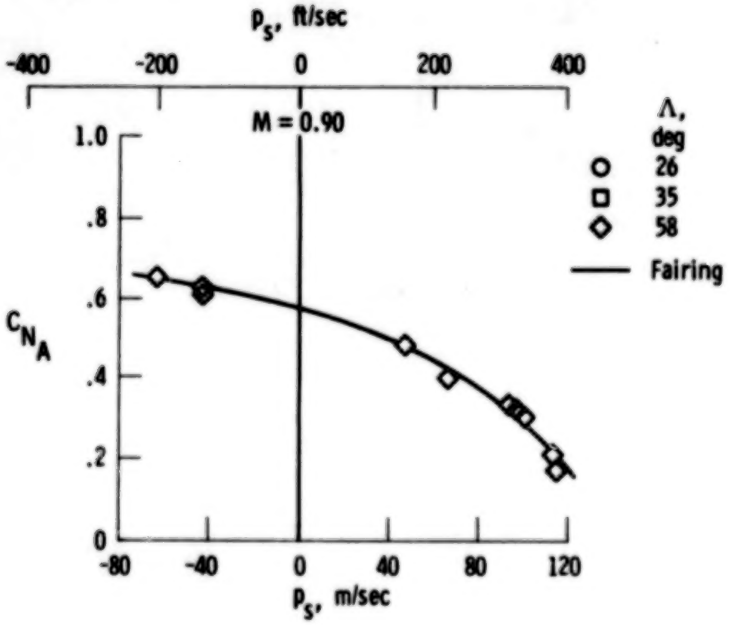


(b) $\bar{q} = 10.5\ kN/m^2\ (220\ lb/ft^2)$.



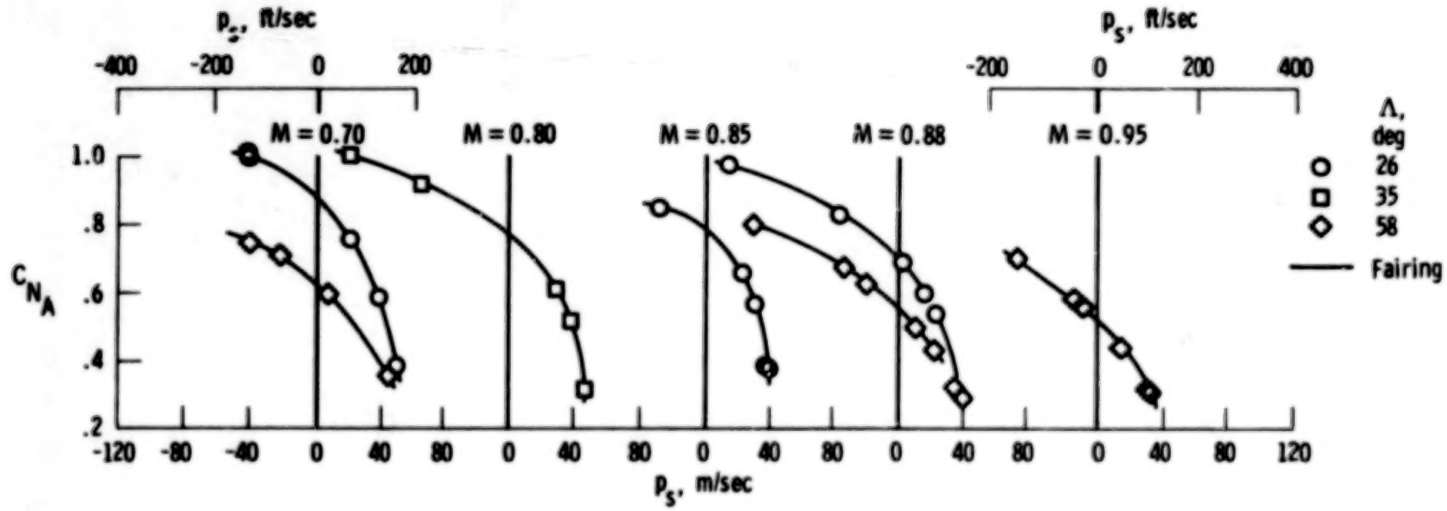
(c) $\bar{q} = 21.6\ kN/m^2\ (450\ lb/ft^2)$.

Figure 32. Continued.



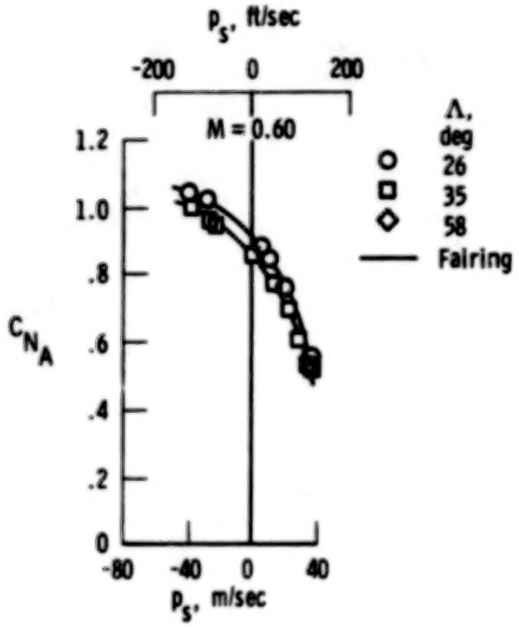
(d) $\bar{q} = 38.3\ kN/m^2\ (800\ lb/ft^2)$.

Figure 32. Concluded.

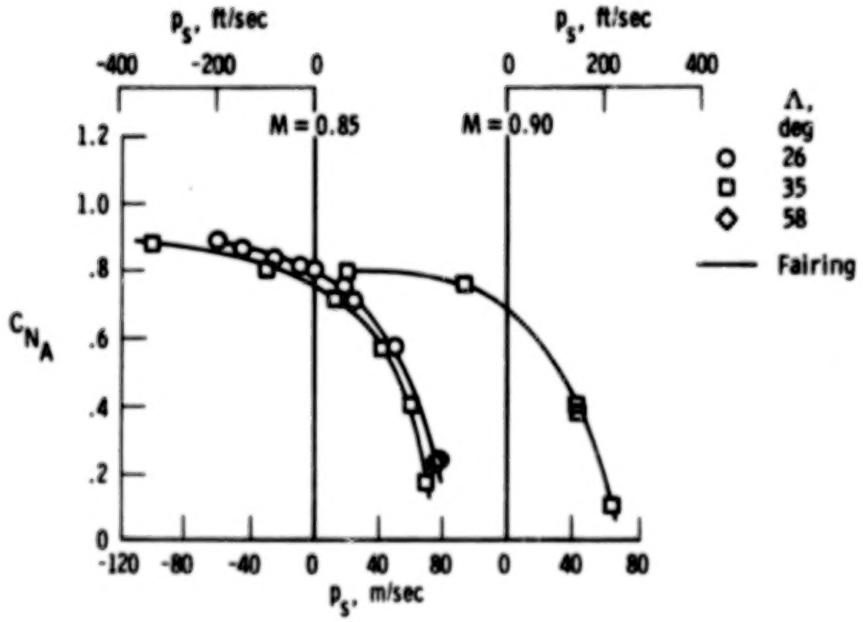


(a) $\bar{q} = 14.4\ kN/m^2\ (300\ lb/ft^2)$.

Figure 33. Specific excess power data for F-111 TACT airplane.

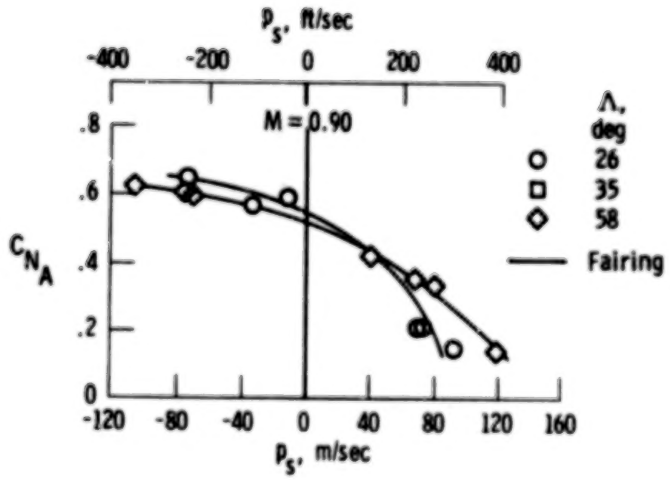


(b) $\bar{q}$ = 10.5 kN/m^2 (220 lb/ft^2).



(c) $\bar{q}$ = 21.6 kN/m^2 (450 lb/ft^2).

Figure 33. Continued.



(d) $\bar{q}$ = 38.3 kN/m^2 (800 lb/ft^2).

Figure 33. Concluded.

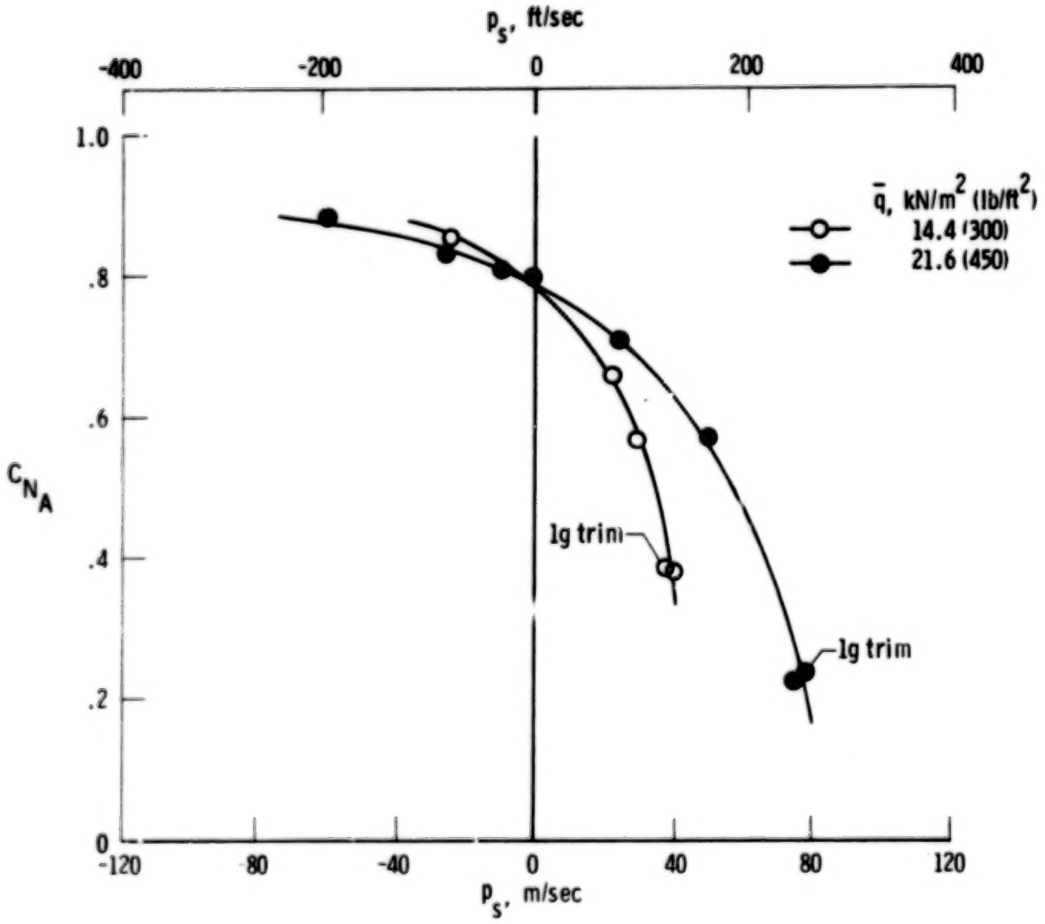


Figure 34. Dynamic pressure effect on specific excess power variation obtained on F-111 TACT airplane at M = 0.85. Λ = 26°.

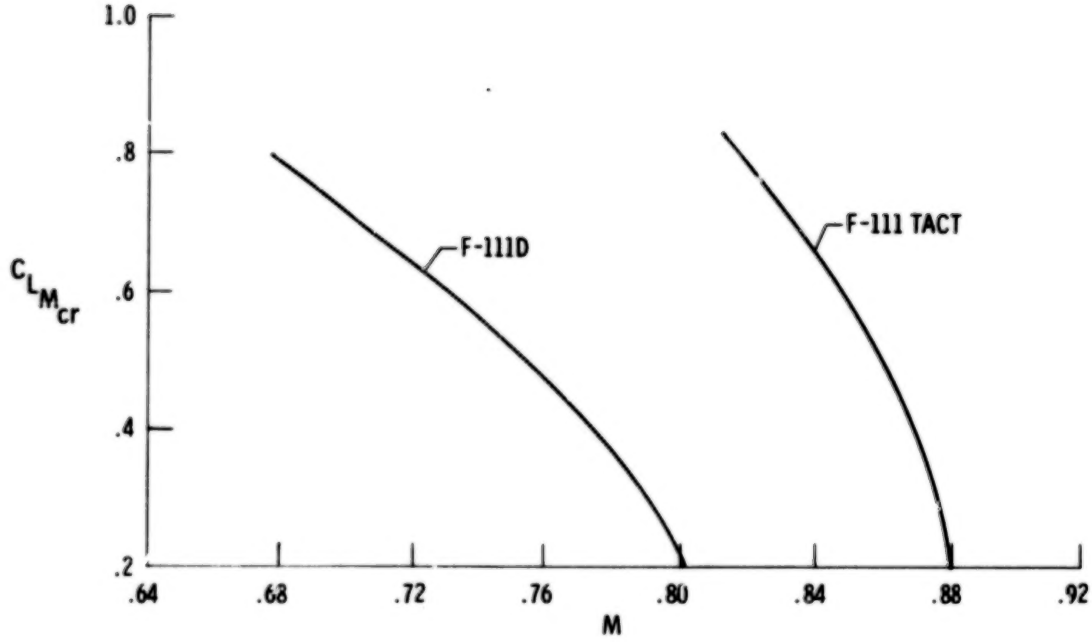


Figure 35. Comparison of drag-rise Mach numbers for F-111D and F-111 TACT models at Λ = 26° (ref. 9).

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15. Supplementary Notes

16. Abstract

A flight research program was conducted to investigate the improvements in maneuverability of an F-111A airplane equipped with a supercritical wing. In this configuration the aircraft is known as the F-111 TACT (transonic aircraft technology) airplane. The variable-wing-sweep feature permitted an evaluation of the supercritical wing in many configurations. The primary emphasis was placed on the transonic Mach number region, which is considered to be the principal air combat arena for fighter aircraft.

An agility study was undertaken to assess the maneuverability of the F-111A aircraft with a supercritical wing at both design and off-design conditions. The evaluation included an assessment of aerodynamic and maneuver performance in conjunction with an evaluation of precision controllability during tailchase gunsight tracking tasks.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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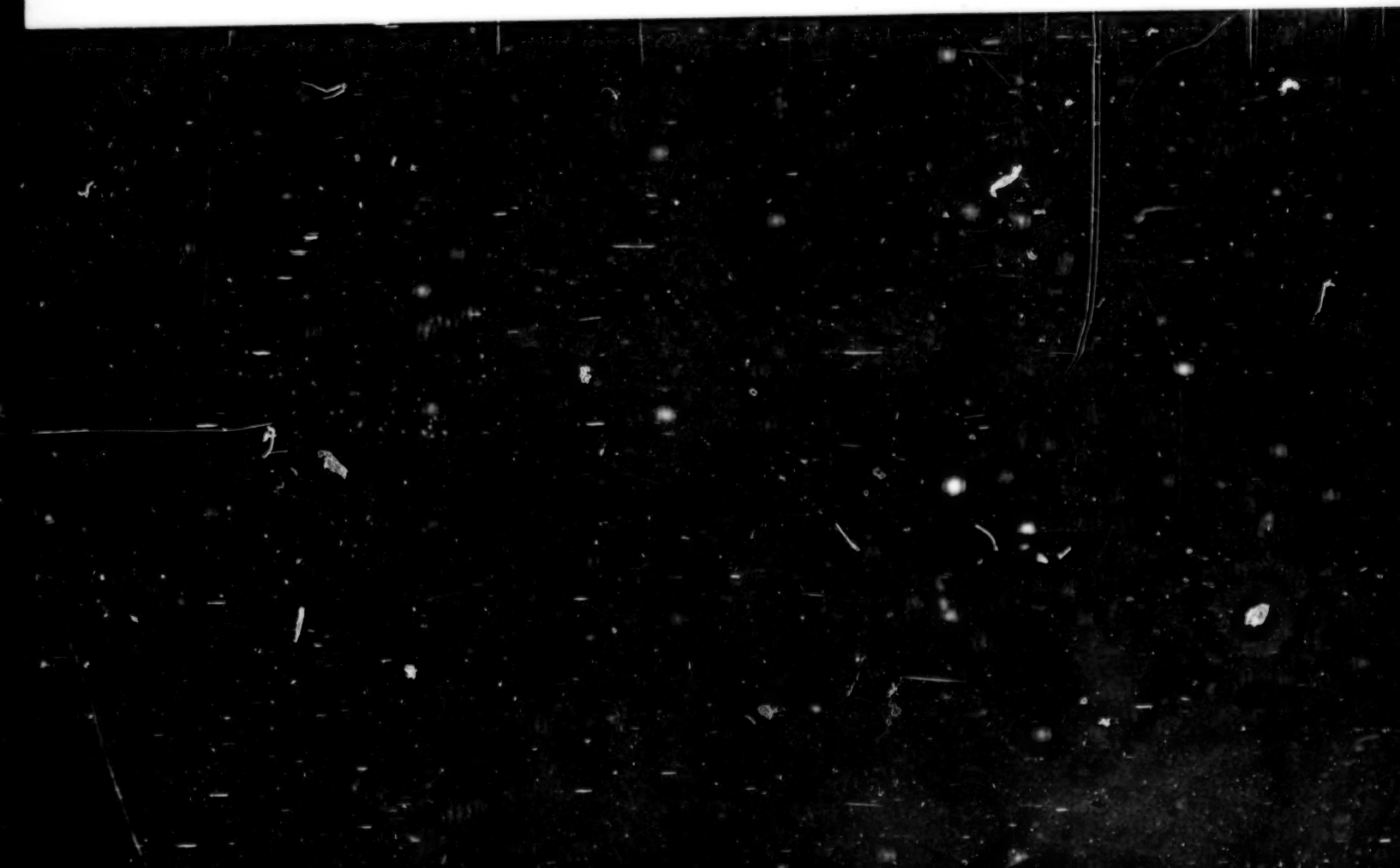

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MAR 16 1979